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Mechanisms Controlling Stem Cell Differentiation

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MECHANISMS CONTROLLING STEM CELL DIFFERENTIATION

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ACTH	Adrenocorticotropic hormone
ADP	Adenosine diphosphate
AdSCs	Adult stem cells
ALDH6A1	Aldehyde dehydrogenase 6 family member A1
AMP	Adenosine monophosphate
AMP-PNP	Adenylyl-imidodiphosphate
aP2	Adipocyte protein 2
ASPN	Asporin
ARS	Alizarin Red S
AVP	Arginine vasopressin
BAT	Brown adipose tissue
BMI	Body mass index
BMP	Bone morphogenetic protein
cAMP	Cyclic adenosine monophosphate
CAN	Ca^{2+}-activated non-selective cation
CD	Cluster of differentiation
CDK6	Cyclin-dependent kinase 6
cDNA	Complementary deoxyribonucleic acid
C/EBPβ	CCAAT/enhancer-binding protein β
CITED1	Cbp/p300-interacting transactivator 1
Col3a1	Collagen alpha-1(III)
CRAC	Ca^{2+} release-activated Ca^{2+} channels
CSCs	Cancer stem cells

DAG	Diacylglycerol
DLX3	Distal-less homeobox 3
DPSCs	Dental pulp stem cells
ER	Endoplasmic reticulum
ERK	Extracellular signal-regulated kinase
ESCs	Embryonic stem cells
FAS	Fatty acid synthase
FIGF	c-fos induced growth factor
Flt1	FMS-like tyrosine kinase 1
Fura-2AM	Fura-2 acetoxymethyl ester
GAPDH	Glyceraldehyde-3-phosphate dehydrogenase
hASCs	Human adipose-derived stem cells
hBMSC	Human bone marrow-derived stem cells
IBMX	3-isobutyl-1-methylxanthine
IL-2	Interleukin 2
IL6R	Interleukin 6 receptor
IP_3R	Inositol-1,4,5-triphosphate receptor
iPSCs	Induced pluripotent stem cells
LPIN1	Lipin 1
LPL	Lipoprotein lipase
LUM	Lumican
MAPK	Mitogen-activated protein kinases
MEPE	Matrix extracellular phosphoglycoprotein
MGP	Matrix γ-carboxyglutamate protein

miRNA	Micro-ribonucleic acid
MMP3	Matrix metallopeptidase 3
MSCs	Mesenchymal stem cells
NFAT	Nuclear factor of activated T-cells
NFE2	Nuclear factor erythroid-derived 2
NMDG	N-methyl-D-glucamine
ORO	Oil Red O
PI3K/Akt/mTOR	Phosphoinositide-3-kinase/Akt/mammalian target of rapamycin
PIP_2	Phosphatidylinositol-4,5-biphosphate
PKA	Protein kinase A
PKC	Protein kinase C
PLC	Phospholipase C
PPARγ	Peroxisome proliferator-activated receptor γ
rDFSCs	Rat dental follicle stem cells
RGS2	G-protein signaling 2
RT-PCR	Reverse transcriptase polymerase chain reaction
Runx2	Runt-related transcription factor 2
SELENBP1	Selenium binding protein 1
SFRP1	Secreted frizzled-related protein 1
shRNA	Short hairpin ribonucleic acid
Smad1	Sma and Mad related family 1
SOCs	Store-operated Ca^{2+} channels
SPP1	Secreted phosphoprotein 1

STIM1	Stromal interaction molecule 1
TG	Thapsigargin
TRPA	Transient receptor potential ankyrin
TRPC	Transient receptor potential canonical
TRPM4	Transient receptor potential melastatin 4
TRPML	Transient receptor potential mucolipin
TRPN	Transient receptor potential *Drosophila* no mechano-potential C
TRPP	Transient receptor potential polycystin
TRPV	Transient receptor potential vallinoid
VDCCs	Voltage dependent Ca^{2+} channels
WIF1	WNT inhibitory factor 1

ABSTRACT

Mesenchymal stem cells are multipotent cells that can differentiate into many cell types. However, the molecular mechanism controlling this process remains unclear. We utilized rat dental follicle stem cells (rDFSCs) and human adipose derived stem cells (hASCs) to study the mechanisms controlling osteogenesis and adipogenesis. Elevations in the intracellular Ca^{2+} concentration are a phenomenon commonly observed during stem cell differentiation but cease after the process is complete. The Transient Receptor Potential Melastatin 4 (TRPM4) is an ion channel that controls Ca^{2+} signals in excitable and non-excitable cells. However, there are no studies on TRPM4 in stem cells. In another study, we investigate the mechanism by which arginine vasopressin (AVP), a neuropeptide hormone secreted mostly from the posterior pituitary gland increased Ca^{2+} signals and inhibited adipogenesis in hASCs.

The overall goal of our studies is to investigate the effect of TRPM4 and AVP on stem cell differentiation and Ca^{2+} signaling. First, we identified TRPM4 gene expression and its characteristics such as Ca^{2+}-activated, voltage dependent and monovalent conducting properties in rDFSCs. Molecular suppression of TRPM4 transformed the normal agonist-induced first and secondary phases of Ca^{2+} signals into a gradual and sustained increase which enhanced osteogenesis but inhibited adipogenesis in rDFSCs. Next, we examined TRPM4's impact on Ca^{2+} signals and adipogenesis in hASCs, which is a more suitable stem cell type for adipogenic studies. Suppression of the TRPM4 diminished the histamine-induced Ca^{2+} signals mainly via H1 receptors. The increases in

intracellular Ca^{2+} were due to influx via voltage-dependent Ca^{2+} channels of the L-type ($Ca_v1.2$) and release from the endoplasmic reticulum (ER). Lastly, we determined the role of AVP on adipogenesis in hASCs. These cells were responsive to AVP stimulation by increasing intracellular Ca^{2+} via V1a receptors, Gq-proteins and the PLC-IP_3 pathway. Both Ca^{2+} release from the ER and influx from the extracellular space contribute to the Ca^{2+} signals. AVP supplementation to the differentiation media decreased the number of adipocytes during adipogenesis. The effect of AVP on adipocyte formation was reversed by the V1a receptor blocker V2255. In conclusion, TRPM4 and AVP control Ca^{2+} signals which affect stem cell differentiation.

CHAPTER 1: STEM CELLS AND Ca^{2+} SIGNALING

1.1 STEM CELLS

Stem cells are cells that have capacity for self-renewal, clonogenic entity and potency [1]. Stem cell research is focused on tissue/adult stem cells, embryonic stem cells and induced pluripotent stem cells. Also, cancer stem cells are being used to develop diagnostic tests and effective anti-tumor therapy [1].

1.1.1 Embryonic stem cells

Embryonic stem cells (ESCs) are pluripotent cells derived from the inner cell mass of the blastocyst that can differentiate into all cell types except placenta [2]. They are promising for tissue engineering because of their proliferation capability and sustained potency. However, there are ethical issues preventing their use. In addition, they can cause tumors and immune rejection after transplanted into patients [3].

1.1.2 Induced pluripotent stem cells

Induced pluripotent stem cells (iPSCs) are somatic cells that are reprogrammed to become pluripotent like ESCs [4]. Yamanaka's group utilized retroviral expression of 4 transcription factors (Oct4, Sox2, Klf4 and c-Myc) in mouse fibroblast to generate embryonic stem cell-like cells [4]. Next, Yu's group utilized Lin-28 instead of c-Myc to induce iPSCs from human somatic cells [5]. Currently, there are various approaches to induce iPSCs such as RNA reprogramming (miRNAs, RNA virion, RNA replicon), protein, polycistron, and non-replicating plasmids (Figure 1.1) [6]. iPSCs have advantages because of the absence of ethical issues. Furthermore, they can differentiate into three germ layers,

proliferate continuously *in vitro*, and can be used for future disease treatment. These cells open new opportunities for regenerative medicine and stem cell modeling of human disease [7]. However, their disadvantages are low reprogramming efficiency, potential for genetic and epigenetic abnormalities, tumorigenicity, and immunogenicity of transplant cells [6-8].

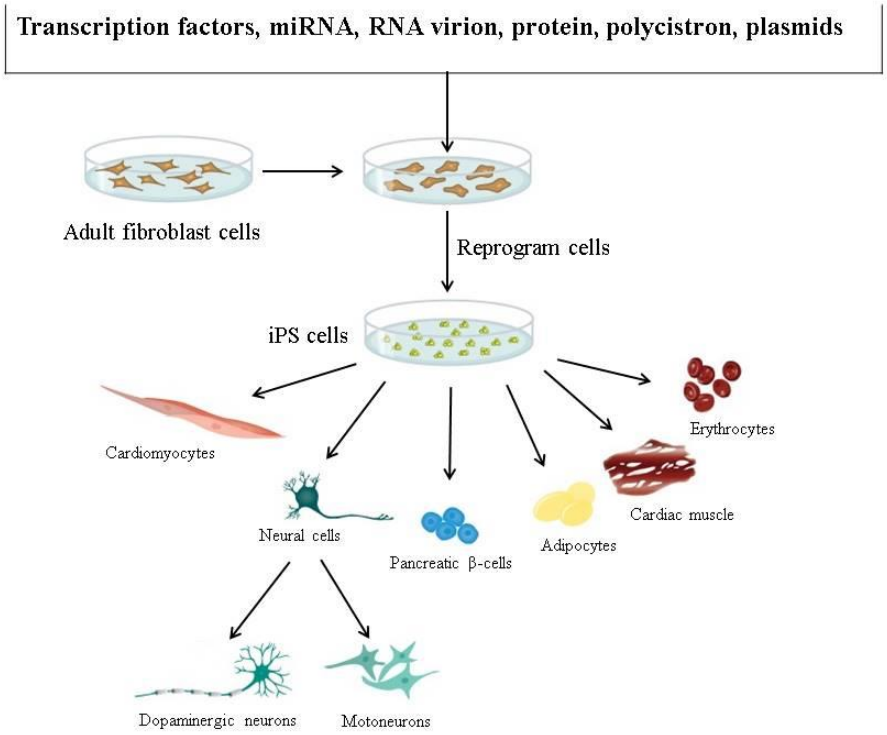

Figure 1.1 Reprogramming pluripotent stem cells (Modified from [9] and http://www.rndsystems.com/Cytokine_cb09i2_induced_pluripotent_stem_cells.aspx.)

1.1.3 Cancer stem cells

Cancer stem cells (CSCs) are derived from damaged or mutated stem cells/progenitor cells that have self-renewal, differentiation and tumor generating properties [1, 10]. Despite their limited numbers, CSCs are a major cause of tumors. They share some similar signaling pathways with normal stem cells like Bmi-1 and

Wnt signaling [10]. They are hereditary, unstable, and highly resistant to chemotherapy and radiotherapy. CSCs are thought to be responsive for tumor regrowth after conventional radiation treatment.

1.1.4 Adult stem cells

Adult stem cells (AdSCs) are cells derived from postembryonic stage tissue with self-renewal capability and multipotency [1]. They include hematopoietic, neural, epithelial, skin, and mesenchymal stem cells (MSCs). This last type is present in many tissues such as bone marrow, dental follicle and fat. DFSCs are isolated from medical waste, unerupted third molars and have advantages such as ease to collect with high efficiency, low morbidity, and good for bone regeneration in osteoporosis [11, 12]. hASCs from adipose tissue have minimal loss of differentiation potential after cryopreservation which make this kind of stem cell a potential source for tissue regeneration [13, 14]. As AdSCs are taken from patients, immune rejection and teratoma will not occur when transplanted back to the same patients. For example, bone marrow-derived stem cells (BMSCs) are used to treat leukemia, lymphoma, and several inherited blood disorders [15].

1.1.4.1 Dental follicle stem cells

The dental follicle is a loose connective tissue around the developing tooth and is composed of different cell populations derived from the cranial neural crest. Bovine dental follicle contains precursor cells that can differentiate into cementum matrix after being transplanted into mice [16, 17]. Dental follicle precursors/stem cells express putative stem cell markers such as nestin, Notch-1, STRO-1, Oct4, and Nanog as well as mesenchymal stem cell-related surface antigens like CD13,

CD29, CD44, CD73, and CD105 [18-20]. Hypoxia increases the growth and differentiation compared to normoxia [21]. DFSCs can proliferate, form colonies and be harvested at a large volume [20, 22, 23]. In addition, they differentiate into adipocytes better than dental pulp stem cells (DPSCs) but have lower potential to form chondrocytes, and osteoblasts [24]. The osteogenic potential of hDFSCs is higher than hASCs while the opposite is observed during adipogenesis [25]. After cryopreservation, many characteristics of DFSCs such as expression of stem cell markers, proliferation, differentiation, apoptosis and transcription-related genes are unchanged [26]. DFSCs lose their osteogenic properties about passage 11 [27]. Under heat-stress culture condition, there is increased cell proliferation, osteogenesis and expression of marker genes such as BMP2, BMP6, Col3a1, Flt1, Runx2 and SPP1 [28]. Under serum-free conditions, DFSCs form spheroid clusters through focal adhesion kinase signaling [29]. Cementoblast formation from DFSCs involves BMP2/7, MAPK and Smad1 pathway when stimulated by enamel matrix derivatives *in vitro* [30]. BMP-9 promotes osteogenesis by activating p38MAPK pathway and inhibiting ERK1/2 activity in rDFSCs [31]. Notch1 signaling is activated by DLX3 during proliferation and self-renewal in hDFSCs and impairs osteogenesis by downregulating BMP2/DLX3 [32, 33]. BMP4 and BMP6 are involved in osteogenic differentiation of DFSCs since they are upregulated after three days in osteogenic induction media [34]. High levels of BMP6 are required to maintain their osteogenic capability because knockdown reduces osteogenesis [27]. Transcription factors such as TP53 improves DFSC proliferation while SP1 stimulates osteogenesis [35]. Early growth response gene 1 increases osteogenesis

in hDFSCs by facilitating BMP2 and DLX3 expression [36]. Purinergic receptor P2X6, P2Y4 and P2Y14 receptors are also involved in osteogenic and adipogenic induction of hDFSCs and hASCs [37].

1.1.4.2 Human adipose-derived stem cells

The origin of hASCs is from the mesoderm layer of the embryo [38]. They are multipotent cells that can differentiate into adipocytes, chondrocytes, osteoblasts, hepatocytes, myocytes, and pancreatic cells [13]. They have fibroblastic morphology and colony-forming unit ability; they share similar surface antigens with other MSCs such as $CD44^+$, $CD73^+$, $CD90^+$, $CD105^+$, $CD45^-$, and $CD31^-$ [39]. The immunogenicity of hASCs after passage 2 fails to show T lymphocyte reaction during *in vitro* expansion [40]. In addition, hASCs can cause dendritic cell tolerance when being co-cultured by inhibiting $CD4^+$ T cell activation [41]. They have normal karyotype, reduced telomerase levels and cease proliferation at passage 30 [42]. hASCs from different donors vary in adipogenic capability [43]. Intracellular Ca^{2+} oscillations in undifferentiated hASCs may be involved in stem cell maintenance and are dependent on Ca^{2+} release and influx [44]. ERK suppression inhibits osteogenesis but induces adipogenesis [45, 46]. Endogenous Wnt signaling inhibits osteogenesis but has no effect on adipogenesis while Notch signaling inhibits adipogenesis [47, 48]. The Hedgehog signaling pathway is involved in adipocyte maturation by reducing C/EBPα and PPARγ expression and insulin sensitivity [49]. Nell-1 signaling crosstalks with the Hedgehog pathway to inhibit adipogenesis [50]. Epidermal and fibroblast growth factors facilitate proliferation and increase adipogenesis and insulin sensitivity [51].

miRNAs, such as miR-17-5p, miR-106a and miR-22 also regulate osteogenesis and adipogenesis [52, 53]. Hypoxia can invoke adipogenesis by stimulating the PI3K/Akt/mTOR pathway [54]. Autologous platelet-rich plasma and insulin treatment stimulate adipogenic differentiation via Akt [55]. Therefore, many signaling pathways control adipogenesis and osteogenesis in AdSCs but the role of Ca^{2+} signaling on differentiation remain largely unknown.

1.2 CALCIUM SIGNALING IN STEM CELLS

Intracellular Ca^{2+} signaling controls many processes such as fertilization, proliferation, development, differentiation, contraction, and secretion [56]. Stem cells have ion channels on their plasma membrane that regulate Ca^{2+} movement into cells. Below is an overview of different Ca^{2+} channels and signaling pathways.

1.2.1 Voltage dependent Ca^{2+} channels

Voltage dependent Ca^{2+} channels (VDCCs) are mostly expressed in excitable cells like neuron, skeletal muscle, and heart cells [57]. Due to the depolarization, VDCCs open to stimulate Ca^{2+} influx into the cells, leading to various cellular responses such as hormone secretion, neurotransmitter release, and muscle contraction [57]. However, there are reports of VDCCs in non-excitable cells such as microglial cells and T lymphocytes [58, 59]. VDCCs may play a role in histamine release from human basophils [60]. In stem cells, hBMSCs express functional L-type VDCCs of the $Ca_v1.2$ type [61, 62]. hASCs also have L-type VDCCs ($Ca_v1.2$) and T-type VDCCs ($Ca_v3.2$) [63]. In rDPSCs, the $Ca_v1.2$ is needed for neural differentiation as knockdown inhibits differentiation [64].

1.2.2 Store-operated Ca^{2+} channels

Store-operated Ca^{2+} channels (SOCs) also known as Ca^{2+} release-activated Ca^{2+} channels (CRAC) are activated by the phospholipase C (PLC) pathway which catalyzes phosphatidylinositol-4,5-biphosphate (PIP_2) to inositol-1,4,5-triphosphate (IP_3) that binds to the ER to promote Ca^{2+} release into the cytoplasm [65]. When the ER is exhausted of Ca^{2+}, stromal interaction molecule (STIM), a Ca^{2+} ER sensor, translocates to SOCs to promote Ca^{2+} influx [66]. This channel is the main Ca^{2+} entry pathway in non-excitable cells [67]. It is highly selective for Ca^{2+} ions and is only permeable to monovalent cations in divalent free cation extracellular solution [68, 69]. Mutation of two conserved negatively charged glutamate residues decreases the Ca^{2+} entry via SOCs in T lymphocytes [70]. The Orai1, Orai2, Orai3 are the main components of SOCs while the first is the pore of the channel [71-73]. Orai1 is a membrane protein with four transmembrane segments with intracellular C and N terminus [70, 71]. Orai1 or Orai2/Orai3 overexpression with STIM1 amplify CRAC currents; Orai1, not Orai2 or Orai3, is inhibited by intracellular Ca^{2+} [73, 74]. Orai1 and STIM1 are important for AVP-induced Ca^{2+} oscillations and entry in rat hepatocytes [75]. The CRAC channel is also regulated by pH because acidification diminishes while alkalization facilitates its activity [76].

1.2.3 The phospholipase C - Inositol triphosphate pathway

Phospholipase C was first reported from amylase secretion in the pancreas treated with acetylcholine and carbamylcholine [77]. Later, PLC was identified as the enzyme catalyzing PIP_2 to IP_3 and diacylglycerol (DAG) [78]. There are 13

PLC family members that are subdivided into 6 classes (β, γ, δ, ζ, ε, and η) [79]. PLCβ, PLCδ and PLCη are linked to Gq-couple receptors; however, PLCγ and PLCζ, are connected to tyrosine-kinase receptors while PLCε is attached to both receptors [79].

Inositol-1,4,5-triphosphate's function was determined when pancreatic acinar cells released ER Ca^{2+} during carbachol stimulation [80, 81]. There are 3 types of IP_3R: IP_3R1, IP_3R2 and IP_3R3 [82]. IP_3R is a major contributor to Ca^{2+} release from the ER in undifferentiated hBMSCs [62]. IP_3-induced Ca^{2+} release is crucial for spontaneous Ca^{2+} oscillations in stem cells [83-85]. Human preadipocytes have all three IP_3Rs that are involved in intracellular Ca^{2+} oscillations [86].

1.3 EFFECT OF TRPM4 ON Ca^{2+} SIGNALING

1.3.1 Overview of TRP channels

Transient receptor potential (TRP) ion channels were first reported in *Drosophila melanogaster* [87]. They are divided into 7 subfamilies: The canonical (TRPC), vallinoid (TRPV), melastatin (TRPM), ankyrin (TRPA), mucolipin (TRPML), polycystin (TRPP), and *Drosophila* no mechano-potential C (TRPN). All channels have six transmembrane segments with the pore region between the 5^{th} and 6^{th} segments and C- and N-terminal domains in the intracellular space (Figure 1.2).

TRPC has 7 members (TRPC1-7) and is the most characterized subfamily. TRPC is activated by DAG from receptor-induced PLC activation, or stimulation of translocation to the plasma membrane, or by depletion of ER Ca^{2+} [88, 89]. It is

involved in different cellular processes such as keratinocyte Ca^{2+} homeostasis, myoblast differentiation and cardiac hypertrophy [90-92].

TRPV is composed of 6 members (TRPV1-6). It is activated by vanilloid, vanilloid-like compounds and heat [93]. The most well-known member is TRPV1 (also known as capsaicin-activated/capsaicin receptor). TRPV1 activation prevents adipogenesis and obesity by increasing energy expenditure [94, 95]. TRPV4 inhibits adipogenesis in TRPV4 knockout mice or wild-type mice treated with a TRPV4 antagonist by improving insulin sensitivity and reducing obesity and adipose inflammation [96].

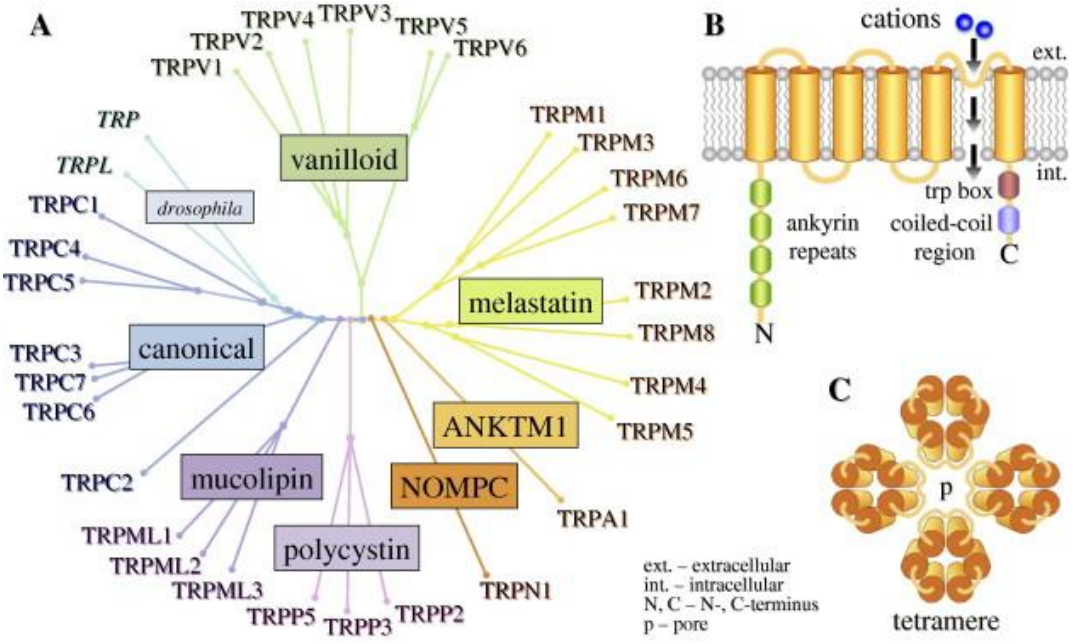

Figure 1.2 TRP family of ion channels (Reprinted with permission from Elsevier Ltd. Authors: Piper Nelson, Andreas Beck and Henrique Cheng. Vet. J. 2011; 187:153-164.)

TRPA includes three *Drosophila*, two *Caenorhabditis elegans* and one mammalian member known as TRPA1. TRPA1 is expressed in chemosensory C-fibers and activated by polygodial, acrolein and crotonaldehyde. They are

involved in inflammatory pain signaling during asthma and chronic obstructive pulmonary disease [87, 97]. TRPA1 knockout or wild-type mice treated with TRPA1 antagonists show reduced pain and inflammation [98].

TRPN is found in *Caenorhabditis elegans, Drosophila* and zebrafish. It is the primary transduction channel in *Drosophila* mechanosensory cilia in both external and chordotonal sensory neurons [99]. TRPML is composed of 3 members (TRPML1-3). They are expressed in intracellular vesicles of the endolysosome system [100, 101]. TRPP is a mechanosensor channel, existing in kidneys and ovaries where it responds to fluid movement in kidney and follicle maturation and differentiation in ovaries [87].

The TRPM subfamily includes 8 members (TRPM1-8). TRPM1 was named after it was found as a tumor suppressor gene in melanoma cells [102]. Mutation of TRPM1 is observed in patients with autosomal-recessive complete congenital stationary night blindness [103]. TRPM2 has a Nudix enzyme domain in the C-terminal that is activated by heat, β-NAD^+, ADP-ribose and hydrogen peroxide, but is suppressed by intracellular ATP [104-107]. It increases Ca^{2+} oscillations and cell proliferation in hBMSCs but has no effect on osteogenesis and adipogenesis [108]. TRPM3 exists in the brain and kidneys where its activity is increased by sphingosine derivatives and hypotonic solution and is involved in Ca^{2+} homeostasis [109, 110]. Among all TRPM channels, only TRPM4 and TRPM5 channels are Ca^{2+} impermeable. In spite of conducting Na^+, they have a profound effect on intracellular Ca^{2+} signals because the depolarization resulting from channel opening controls the activation of Ca^{2+} channels in the plasma membrane. TRPM5, which

shares 50% sequence homology with TRPM4, is found in the intestines, taste receptors, brain, and pancreatic β cells [111, 112]. TRPM2 and TRPM5 control Ca^{2+} signals and insulin secretion from pancreatic β cells [113-116]. TRPM6 and TRPM7 are also 'chanzymes' with alpha-kinase domain in the C-terminal region and facilitates Ca^{2+} and Mg^{2+} influx. TRPM6 is expressed in intestinal epithelia and kidney tubule cells and is important for Mg^{2+} homeostasis [117]. Mutation of TRPM6 induces hypomagnesemia with secondary hypocalcemia and patients with this defect have abnormal renal Mg^{2+} excretion [118]. TRPM6 knockout mice have lower survival rates, neural tube defects, and infertility [119]. TRPM7 is essential for MSC and ESC survival, proliferation as well as osteoblast differentiation and osteogenesis [120-122]. It is important for proliferation and adipogenesis of preadipocytes, as channel suppression inhibits these processes [123]. TRPM8 is predominantly expressed in dorsal root ganglia and neurons from trigeminal ganglia and is activated by cold and cooling agents such as menthol and icilin [124, 125]. Brown adipose tissue (BAT) express TRPM8, and when activated, it will enhance uncoupling protein 1 production for thermogenesis and prevention of obesity [126].

1.3.2 TRPM4

TRPM4 is a Ca^{2+}-activated non selective cation (CAN) channel [127]. They form tetramers to make a functional unit. Its selectivity filter is linked to six amino acids between the 5^{th} and 6^{th} transmembrane helices. Mutations of Glu^{981}, Asp^{982} and Asp^{984} to Ala shifts the voltage dependency to a more positive potential and replacement of Gln^{977} with Glu enables Ca^{2+} permeability [128]. Its structure

includes ATP, calmodulin and protein kinase C (PKC) binding sites [129]. Two divalent cation binding sites and negatively charged amino acids in the C-terminus help preserve the normal Ca^{2+} sensitivity [130]. TRPM4 is ubiquitously expressed throughout the body [102, 127, 131-136].

TRPM4's activity is enhanced by decavanadate and BTP2 [137, 138]. TRPM4's desensitization is delayed by Mg^{2+}-ATP, calmodulin, PIP_2 or phosphorylation via PKC [129, 139, 140]. The channel is also activated by high temperature [141]. Hydrogen peroxide inhibits TRPM4 desensitization [142]. Intracellular nucleotides (ATP, ADP, and AMP), spermine, glibenclamide, flufenamic acid and 9-phenanthrol inhibit TRPM4 [143, 144]. 9-phenanthrol is the most specific TRPM4 inhibitor since it does not block TRPM5 or TRPM7 [145].

TRPM4 was first characterized as a Ca^{2+}-activated nonselective cation channel with three typical features such as Ca^{2+} activation, voltage dependency and monovalent cation conductance [127]. In excitable cells, TRPM4 depolarizes the cell membrane and facilitates VDCC opening while the opposite effect occurs in non-excitable cells as it decreases the driving force for Ca^{2+} entry via SOCs [127, 146]. In T lymphocytes, it decreases Ca^{2+} signals by inhibiting SOCs and IL-2 production [147]. TRPM4 expression is lower in T helper type 1 compared to T helper type 2 cells; inhibition of the channel increases Ca^{2+} signals, NFATc1 nuclear localization, and IL-2 production but decreases motility in T helper type 2 [148]. Mast cells from TRPM4 knockout mice exhibit enhanced Ca^{2+} entry and proinflammatory mediators such as leukotriene C_4, D_4, E_4 [149, 150]. TRPM4 is also important for dendritic cell migration because TRPM4 knockout impairs this

process [151]. It is essential for umbilical cord endothelial cell migration [152]. TRPM4 also facilitates cell proliferation in Hela cells, a cervical cancer-derived cell line [132]. In excitable cells, TRPM4 stimulates myogenic vasoconstriction of cerebral artery myocytes as channel inhibition reduces myogenic tone and impairs autoregulation [153, 154]. TRPM4 is upregulated in vascular endothelium after hypoxia/ischemia *in vitro* and *in vivo* and channel inhibition enhances angiogenesis, and capillary integrity [155]. Spontaneously hypertensive rats have higher TRPM4 expression in ventricular cardiomyocytes compared to normotensive rat [156]. It contributes to the action potential in atrial and ventricular cardiomyocytes [157, 158]. TRPM4 prevents bradycardia because channel blockers decrease the action potential rate in the sinus node [159]. Our lab characterized functional TRPM4 channels in pancreatic α and β cells where it facilitates VDCC opening to increase Ca^{2+} signals and glucagon and insulin secretion [146, 160]. TRPM4 is up-regulated after spinal cord injury and subarachnoid hemorrhage [161-164]. TRPM4 knockout mice are hypertensive due to increased catecholamine secretion from adrenal chromaffin cells [131]. Hypoxia opens L-type VDCCs and increases intracellular Ca^{2+} concentration and TRPM4 activity to generate inspiratory bursts, synaptic drive currents in pre-Bötzinger complex [165]. The channel contributes to the pathogenesis of inflammation and neuronal injury in autoimmune encephalomyelitis and multiple sclerosis [134]. It plays a role in producing the slow inward cation current in cerebral Purkinje cells because TRPM4 knockout reduces current amplitude compared to wild-type mice [135]. TRPM4 may regulate K^+ transport during endolymph formation in strial marginal cells and

in inner hair cells in mouse cochlea [136]. TRPM4 missense mutation is observed in South African Afrikaner pedigree with progressive familial heart block type 1 [166]. Another TRPM4 mutation is observed in patients with Brugada syndrome [167].

1.4 AVP AND Ca^{2+} SIGNALING

1.4.1 Structure

The structure of AVP varies among species (Table 1.1). It is a nine amino acid peptide with one disulfide bond between the 1st and 6th position and Arg in the 8th position in most species.

1.4.2 Biosynthesis, storage and release

AVP is synthesized in magnocellular neurons of the supraoptic and paraventricular nuclei as a large precursor molecule. Moreover, the synthesis is directed by three exons separated by two introns: exon 1 (residues 1 through 21) for the signal peptide AVP and N-terminal end of the neurophysin; exon 2 for the middle portion of neurophysin II (residues 22 through 88); exon 3 for the C-terminal end of neurophysin II (residues 89 through 107) and a 39-residue glycopeptide called copeptin (Figure 1.3). After synthesis, the preprovasopressin is cleaved into the signal peptide and pro-vasopressin and stored into secretory vesicles in the Golgi apparatus, followed by splitting into AVP and neurophysin II [168, 169]. Neurophysin II is important for targeting, packaging and storing before it is released into the blood [170]. Under nerve impulses, the vesicles are transported down the axon via exocytosis; subsequently, AVP and neurophysin separate after leaving the nerve terminals [171]. In addition, AVP is synthesized in

other tissues such as sympathetic ganglia, heart, ovaries, adrenal gland, testis, thymus and pancreas [172-178].

Table 1.1 Structure of AVP in different species (Modified from [179].)

S — S Cys-Tyr-Phe-Gln-Asn-Cys-Pro-Arg-Gly-NH_2	Arginine vasopressin (AVP)	Most mammals
S — S Cys-Tyr-Phe-Gln-Asn-Cys-Pro-Lys-Gly-NH_2	Lysine vasopressin (LVP)	Pigs, hippos, warthogs, some marsupials
S — S Cys-Phe-Phe-Gln-Asn-Cys-Pro-Arg-Gly-NH_2	Phenypressin	Some marsupials
S — S Cys-Tyr-Ile-Gln-Asn-Cys-Pro-Arg-Gly-NH_2	Vasotocin	Non-mammals
S — S Cys-Phe-Ile-Arg-Asn-Cys-Pro-Lys-Gly-NH_2	Lys-conopressin	Great pond nail (*Lymnaea stagnalis*)
S — S Cys-Ile-Ile-Arg-Asn-Cys-Pro-Arg-Gly-NH_2	Arg-conopressin	Striated cone (*Conus striatus*)
S — S Cys-Phe-Val-Arg-Asn-Cys-Pro-Thr-Gly-NH_2	Annetocin	Red worm (*Eisenia foetida*)
S — S Cys-Leu-Ile-Arg-Asn-Cys-Pro-Arg-Gly-NH_2	Inotocin	Migratory locust (*Locusta migratoria*)

1.4.3 Receptors and mechanisms of action

AVP exerts its effect in the body by binding to three types of receptors: V1a, V1b and V2. AVP receptors are G-protein-coupled with seven transmembrane domain [180]. V1a receptors are the most prevalent in the body ranging from smooth muscle, mesangial cells, and lymphocytes to astrocytes [181-184]. The V1a receptors in humans and rats are 418 and 394 amino acids, respectively [185, 186]. V1b receptors are present mainly in the anterior pituitary, adrenal medulla, and pancreatic α and β cells [187-190] . Human and rat V1b receptors encode 424 and

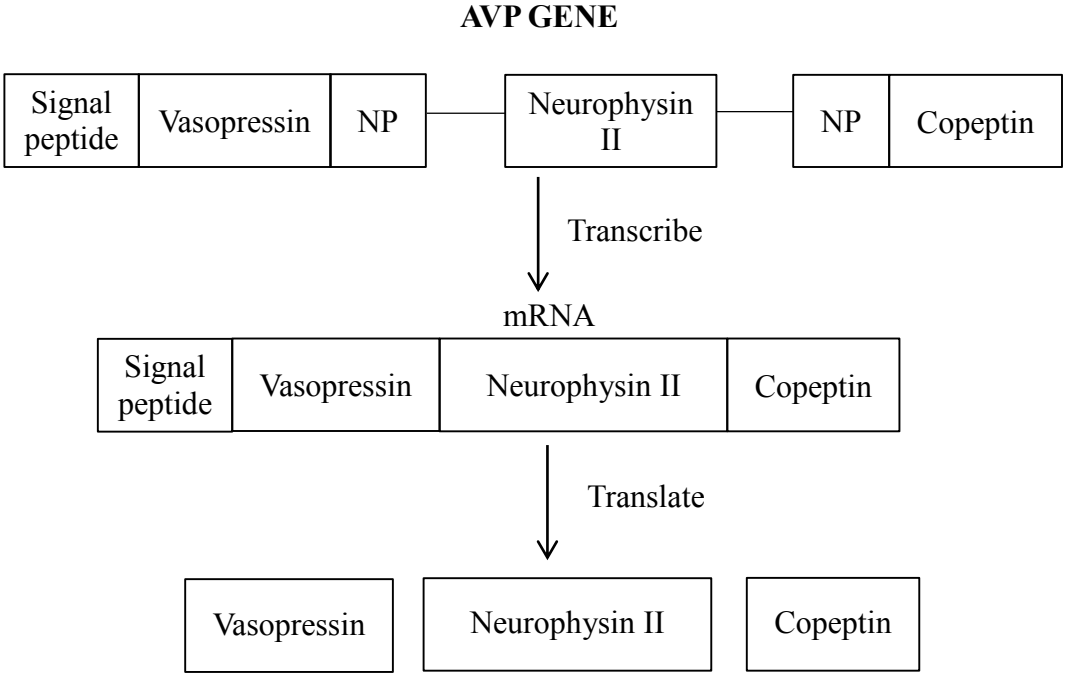

Figure 1.3 AVP synthesis (Modified from [179].)

425 amino acids, respectively and share 81% identity [187, 191]. Human V1b has 45% and 39% homology with the V1a and V2 receptors [187]. The V2 receptor is found in the renal distal and principal cells of the collecting ducts [192, 193]. It is also found in endothelial cells and skeletal muscle of the lungs [194]. This receptor in humans and rats contains 371 and 370 amino acids with over 80% homology [192, 193, 195]. The signaling cascade via V1 receptors is by the Gq-protein-PLC-IP_3 pathway that increases intracellular Ca^{2+} for a number of cellular processes [196, 197]. V1a receptors are linked to behavior and aggression [197]. On the other hand, the V1b receptor has a critical role in behavior and episodic memory [198]. V1a and V1b receptors are associated with food and alcohol intake, circadian rhythm, and thermoregulation [197]. V2 receptors are coupled to Gs proteins that activate the cAMP-PKA pathway and induce translocation of aquaporin-2 channels

for water reabsorption in the kidneys [192, 199]. Because of its effect in the kidneys, AVP is also called as antidiuretic hormone. The factors affecting AVP secretion are listed in Table 1.2.

Table 1.2 Factors regulating AVP secretion (Modified from [179].)

Stimulation	Inhibition
Major factors	
Hyperosmolality Hypovolemia Hypotension	Hypoosmolality Hypervolemia
Additional factors	
Cerebrospinal fluid sodium increase Nausea, vomiting Stressor, lactation Hyperthermia Ageing	Hypothermia α-adrenergic agonists γ-aminobutyric acid Alcohol Cortisol Iodothyronines Atrial natriuretic peptide
Drugs: Nicotine, Opiates, Barbiturates, Sulfonylureas, Antineoplastic agents, Neurosteroids	Apelin AVP

1.4.4 Agonists, blockers and their importance in research and clinical application

AVP agonists and antagonists are used for treating many diseases. Desmopressin, an AVP analog is used to treat diabetes insipidus [200]. V1a antagonists are used in the treatment of ocular hypertension, congestive heart failure, myocardial infarction, and preterm labor. V1b antagonists improve anxiety and depression. V2 antagonists are used in hyponatremia, polycystic kidney diseases and cirrhotic ascites [201, 202].

1.5 STATEMENT OF PROBLEMS AND SPECIFIC AIMS

In the United States, the direct expenses of osteoporotic fractures are estimated to be around $18 billion each year [203]. In addition, the total cost related

to adolescent obesity is estimated to be $254 billion [204]. Therefore, understanding the mechanisms controlling osteogenesis and adipogenesis from stem cells is important for bone healing and obesity prevention. However, there is limited information regarding the effects of Ca^{2+} signaling on stem cell differentiation. Calcium oscillations stimulate transcription factors and gene expression [205]. They are important for the G_1/S phase of the cell cycle and originate from IP_3-mediated Ca^{2+} release from the ER in ESCs and BMSCs [83, 85]. In addition, they are observed during stem cell differentiation but cease at the end of this process [84, 206]. Physical manipulation of Ca^{2+} oscillations increases osteogenesis in hBMSCs [207]. As a result, the overall goal of this dissertation is to investigate the effect of TRPM4 and AVP on Ca^{2+} signaling for controlling stem cell differentiation. Currently, there are no reports of TRPM4 in any type of stem cell. Therefore, we hypothesize that TRPM4 is a critical regulator of Ca^{2+} signaling and stem cell differentiation. Our first aim is determine the role of TRPM4 in rDFSCs (Chapter 2) and hASCs (Chapter 3). Furthermore, AVP induces myogenesis and T cell differentiation via V1 receptors; however, there is no information in hASC differentiation [182, 208]. Our lab found that AVP increases intracellular Ca^{2+} concentration in hASCs. Consequently, we hypothesize that hASCs have AVP receptors which are involved in Ca^{2+} signaling and adipogenic differentiation. Our second aim is to characterize the mechanism by which AVP increases intracellular Ca^{2+} and its role in adipogenesis in hASCs (Chapter 4).

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CHAPTER 2: TRANSIENT RECEPTOR POTENTIAL MELASTATIN 4 CHANNEL CONTROLS CALCIUM SIGNALS AND DENTAL FOLLICLE STEM CELL DIFFERENTIATION*

2.1 INTRODUCTION

Stem cell therapy offers a promising approach in providing an advanced and reliable therapeutic strategy for tissue regeneration and disease treatment. However, fundamental processes controlling the fate of stem cells are not well understood. Dental follicle stem cells (DFSCs) are derived from the neural crest and give origin to the periodontal ligament (PDL) [1, 2]. These cells are multipotent and can differentiate into various cell types including osteoblasts, adipocytes, and neurons [3]. In addition, they can be easily obtained from extracted third molars that are usually discarded as medical waste. Therefore, DFSCs represent an alternative source of stem cells for tissue regeneration. The transient receptor potential (TRP) proteins are a family of ion channels initially identified in the *Drosophila melanogaster* visual system [4]. Despite intensive research, information regarding their function in stem cells remains largely unknown. The melastatin subfamily of TRP channels is composed of eight members (transient receptor potential melastatin [TRPM1–8]), with TRPM4 and TRPM5 being the only non-calcium conducting channels [5, 6]. Both are permeable mainly to Na^+, resulting in depolarization upon channel activation. The ability of TRPM4 to depolarize cells transforms the normal intracellular Ca^{2+} oscillations into sustained

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Ca^{2+} increases in T lymphocytes [7]. This is due to a decrease in the driving force for Ca^{2+} entry via store-operated Ca^{2+} channels (SOCs), the main pathway for Ca^{2+} entry in nonexcitable cells, such as DFSCs of mesenchymal origin [3]. Of the TRPMs, only the TRPM7 has been reported in stem cells. It is essential for bone marrow-derived mesenchymal stem cell (MSC) proliferation and survival and is required for early embryonic development [8, 9].

Oscillations in the intracellular Ca^{2+} concentration ($[Ca^{2+}]_i$) are commonly observed during stem cell differentiation, and there is evidence that they may control the differentiation process. Physical manipulation of Ca^{2+} signals with noninvasive electrical stimulation enhances Ca^{2+} entry and osteodifferentiation of human MSCs (hMSCs; [10]). That study suggests that increased Ca^{2+} entry is a result of activation of G protein-coupled receptors and the opening of Ca^{2+} channels. In addition, activation of gene transcription by nuclear factor of activated T-cells (NFAT) in immune cells appears to be controlled by the shape and frequency of the Ca^{2+} signals [7, 11]. Interestingly, both Ca^{2+} signals and NFAT-activated gene transcription disappear at the completion of adipogenesis in hMSCs [12]. Similar observations have been made during the terminal stages of osteoblast differentiation [10], implying that Ca^{2+} signals may be important for directing and terminating the process. Furthermore, oscillations in the $[Ca^{2+}]_i$ control the transition from the G_1 phase to the S phase of the cell cycle to preserve embryonic stem cell (ESC) pluripotency [13]. Therefore, the question of how Ca^{2+} signals control stem cell differentiation is fundamentally important.

The TRPM4 channel is a widely expressed protein present in both electrically excitable and nonexcitable cells. Patch-clamp recordings revealed that it is a Ca^{2+}-activated nonselective cation (CAN) channel, inhibited by nucleotides and polyamines [5, 14]. Although not permeable to Ca^{2+}, TRPM4 has a significant impact on Ca^{2+} signals because it provides a mechanism that allows cells to depolarize in a Ca^{2+}-dependent manner. In nonexcitable cells such as undifferentiated stem cells, TRPM4-mediated depolarization decreases the driving force for Ca^{2+} entry through SOCs, whereas in excitable cells (e.g., neuron, endocrine, or cardiac muscle), TRPM4 has the opposite effect by providing the depolarization necessary for the opening of voltage-dependent Ca^{2+} channels. Previous studies identified SOCs in hMSCs and mESCs [15, 16]. In fact, molecular suppression of TRPM4 increases both Ca^{2+} entry via SOCs and interleukin 2 (IL-2) production in nonexcitable T lymphocytes [7]. Studies in excitable cells revealed a significant reduction in insulin secretion during glucose stimulation in pancreatic β-cells after TRPM4 knockdown [17]; this reduction results from a decrease in the magnitude of the Ca^{2+} signals [18]. A similar observation was made in glucagon secreting α-cells [19]. In addition to the effects in immune and islet cells, the control of Ca^{2+} signals by TRPM4 is critical for myogenic constriction of cerebral arteries, migration of dendritic cells, and cardiac function [20–22]. Given the importance of Ca^{2+} signals for stem cell differentiation, it is possible that ion channels such as TRPM4 could be involved in their regulatory mechanism.

In this study, we investigated the role of TRPM4 in differentiation of rat DFSC, a MSC from the first molar tooth. We examined TRPM4 gene expression

by reverse transcriptase polymerase chain reaction (RT-PCR) and tested whether currents with the characteristics of those known for this channel could be detected using the patch-clamp technique. To gain insight into TRPM4 function, we generated stable knockdown cells via short hairpin RNA (shRNA). These cells were then used in cell proliferation, Ca^{2+} imaging analysis, and differentiation experiments. Finally, we performed whole genome microarray analysis to examine potential genes regulated by TRPM4 during DFSC differentiation.

2.2 MATERIALS AND METHODS

2.2.1 Reagents

All reagents were purchased from Sigma-Aldrich (St. Louis, MO, http://www.sigmaaldrich.com), except for fura-2 acetoxymethyl ester (Fura-2AM), which was from Molecular Probes (Eugene, OR, http://probes.invitrogen.com).

2.2.2 Cell culture

DFSCs of the first mandibular molar were harvested from Sprague–Dawley rat pups 5–7 days postnatal and cultured according to published methods [23]. Cells were grown in α-minimum essential medium (MEM) supplemented with 20% FBS and aerated with 5% CO_2 and 95% air at 37°C. Experiments were performed with cells from passages 2 through 8. MC3T3-E1 preosteoblast cells were grown in α-MEM supplemented with 10% fetal bovine serum (FBS) and cultured as described for DFSCs. Human adipocyte stem cells (hACSs) were maintained in Dulbecco's modified Eagles medium (DMEM)/Ham's F-12 medium (Sigma-Aldrich) with 10% FBS and aerated with 5% CO_2 at 37°C. All experiments were performed with cells from passages 6 through 8.

2.2.3 Induction and detection of cell differentiation

2.2.3.1 Osteogenesis

Cells were induced with osteogenic medium, consisting of DMEM-LG supplemented with 10% FBS, 10 nM dexamethasone, 0.1 mM ascorbic-acid-2-phosphate, and 10 mM β-glycerophosphate. The medium was changed every 4 days during osteogenesis. After a 14-day period, the medium was aspirated, and the cultures were washed twice with phosphate buffered saline (PBS), fixed with 10% formaldehyde, washed again with distilled water, and incubated with 1% Alizarin Red S (ARS) in dH_2O. After incubation, the staining solution was removed, and the cultures were washed with distilled water to remove excess dye. Stained monolayers were visualized by phase contrast microscopy with an inverted microscope (Zeiss, Thornwood, NY, http://microscopy.zeiss.com).

2.2.3.2 Adipogenesis

Cells were induced with adipogenic medium containing DMEM-LG supplemented with 10% FBS, 50 μg/ml ascorbic acid, 0.1 μM dexamethazone, and 50 μg/ml indomethacin. Adipogenesis was determined by oil red O (ORO) staining. Briefly, cells were washed with PBS, fixed with 10% formalin for 10 minutes, washed twice with dH_2O, and incubated with 60% isopropanol for 5 minutes. Cells were then stained with ORO solution for 5 minutes and washed again to remove excess dye. The presence of lipid droplets was visualized by phase contrast microscopy with an inverted microscope.

2.2.4 RT-PCR

RNA was extracted from DFSCs, hASCs, MC3T3-E1 cells, and bone tissue

using the RNAqueous-4PCR kit according to manufacturer's instructions (Ambion, Austin, TX, http://www.ambion.com). The RNA was purified with DNase 1 treatment. Reverse transcription was performed with MMLV-Reverse Transcriptase. PCR was performed with Ambion's RETROscript kit and rat primers with the sequences listed (forward/reverse [5′–3′]): TTGGCATACTGGGAGACG CA/GGCCCAAGATCGTCATCGT (TRPM4; 301 bp); CAAGTGTGACATGGT GGCCATCTT/GCTCAGGTGGCTGAGCAGGAT (TRPM5; 600 bp); GCAAAT GACTCCACTCTC/GATTCTCTCTTCACTCCCAG (TRPM7; 422 bp). Rat glyceraldehyde-3-phosphate dehydrogenase (GAPDH) (420 bp) and ultrapure water were used as positive and negative controls, respectively. The human primers (forward/reverse [5′–3′]) were: AGCATGGTGCCGGAGAA/GGTGTCTCTATT CCGGACCACA (TRPM4; 600 bp); CAGAACATCACCTCACACCAG/GGTT CTCGCTCTTCTGGTTC (TRPM5; 640 bp); TGAAACGAGTGAGTTCTCTTG CTG/CACAGGTGTAAATGGAATGCTC (TRPM7; 309 bp); AACAGCGACAC CCACTCCTC/GGAGGGGAGATTCAGTGTGGT (GAPDH; 258 bp).

2.2.5 Electrophysiology

Cells were maintained in standard modified Ringer's solution of the following composition (in mM): NaCl 140, KCl 2.8, $CaCl_2$ 1, $MgCl_2$ 2, glucose 4, HEPES-NaOH 10, pH 7.2 adjusted with NaOH. The standard internal solution contained (in mM): Cs-glutamate 120, NaCl 8, $MgCl_2$ 1, Cs-BAPTA 10, HEPES-CsOH 10, pH 7.2 adjusted with CsOH. The internal solution's buffered Ca^{2+} concentration was adjusted as necessary with $CaCl_2$ (calculated with WebMaxC http://www.stanford.edu/~cpatton webmaxcS.htm/). The Na^+-free

modified Ringer's solution contained (in mM): choline-Cl 140, KCl 2.8, $CaCl_2$ 1, $MgCl_2$ 2, glucose 4, HEPES-CsOH 10, pH 7.2 adjusted with CsOH. The osmolarity of the solutions were approximately 300 mOsm/L. TRPM4 currents were recorded in the tight-seal whole-cell configuration mode at 21°C–25°C. High-resolution current recordings were acquired by a computer-based patch-clamp amplifier system (EPC-10, HEKA, Lambrecht, Germany, http://www.heka.com). Patch pipettes had resistances of 4–7 MΩ and were coated in Sigmacote silicon solution (Sigma-Aldrich). Immediately following establishment of the whole-cell configuration, voltage ramps of 50 millisecond duration spanning the voltage range of −100 to +100 mV at a rate of 0.5 Hz over a period of 300–600 seconds. All voltages were corrected for a liquid junction potential of 10 mV between external and internal solutions, calculated with Igor PPT Liquid Junction Potential software (Wavemetrics, Portland, OR, http://www.wavemetrics.com).

2.2.6 Generation of TRPM4 knockdown cells

Lentivirus plasmids were obtained from Sigma-Aldrich in a pLKO.1 backbone and contained either nonspecific control (SHC002) or TRPM4-specific shRNA (SHDNA-NM_175130, TRCN0000068684 and TRCN0000068686) under the control of the U6 promoter, plus the puromycin resistance and green fluorescent protein (GFP) reporter genes. Cells were selected in 1 μg/mL puromycin for 1 week, and transduction efficiency was determined by FACScan flow cytometry (BD Biosciences, Franklin Lakes, NJ, http://www.bdbiosciences.com) to sort GFP^+ cells. Stably transduced cells were used for functional experiments.

2.2.7 Cell proliferation assay

An (3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide (MTT) assay was used to compare the proliferation rates between control and TRPM4 knockdown cells. One week following lentiviral transduction 10^4 cells per well were seeded into three 96-well plates and cultured in normal growth medium for 3 days. Cells were then placed in osteogenic or adipogenic medium and analyzed by an MTT-based assay kit (Bioassay Systems, Hayward, CA, http://www.bioassaysys.com) at 48, 72, and 96 hours. MTT solution was added to each well and incubated at 37°C for 4 hours. Then, solubilization buffer was added to dissolve the insoluble formazan product. The absorbance at 550 nm was measured with an Ultramark Microplate Imaging System (BioRad, Hercules, CA, http://www.bio-rad.com). Cell proliferation was expressed as the absorbance of the cells minus the background.

2.2.8 Calcium imaging analysis

Cells were loaded with 5 μM Fura-2AM for 30 minutes at 37°C. A Ca^{2+}-imaging buffer containing (in mM) NaCl 136, KCl 4.8, $CaCl_2$ 1.2, $MgSO_4$ 1.2, HEPES 10, glucose 4, and 0.1% BSA at a pH of 7.3 was used for Fura-2AM loading and perfusion throughout imaging experiments. Calcium measurements were obtained with a dual excitation fluorometric imaging system (TILL-Photonics, Gräfelfingen, Germany, http://www.till-photonics.com) controlled by TILLvisION software. Fura-2AM-loaded cells were excited by wavelengths of 340 nm and 380 nm. Fluorescence emissions were sampled at a frequency of 1 Hz and computed

into relative ratio units of the fluorescence intensity of the different wavelengths (F_{340}/F_{380}).

2.2.9 Alkaline phosphatase activity

Quantification of alkaline phosphatase (ALP) enzyme activity at different time points during osteogenesis was made with an ALP assay kit (BioChain, Newark, CA) according to the manufacturer's instructions. Differentiation experiments were performed in quadruplicate in a 24-well plate (four wells per time point) and repeated three times. The cells were washed in PBS and lysed with 0.5 ml 0.2% Triton X-100 in distilled water prior to ALP activity determination. Samples were assayed in duplicate in a 96-well plate and analyzed at 405 nm with a microcount plate reader BS10000 (PerkinElmer, Waltham, MA, http://www.perkinelmer.com).

2.2.10 Microarray analysis

Raw/normalized intensity values and the log-ratios of all possible pairwise comparisons were preprocessed by the microarray manufacturer (PhalanxBio Inc., Belmont, CA, http://www.phalanxbiotech.com). The genes that were associated with osteogenesis or adipogenesis and affected by TRPM4 knockdown were selected based on the following two criteria: first, genes displaying at least twofold upregulation/downregulation during cell differentiation in either cell population (minimum absolute fold-change ≥2 between control cells prior to differentiation [C0] and after 14 days [C14] and between TRPM4 knockdown cells prior to differentiation [KD0] and after 14 days [KD14]). Second, fold change differences in genes exhibiting differential upregulation/downregulation between control and

knockdown cell populations during cell differentiation (i.e., differences that exist between fold-change values found in control and knockdown cells).

Following gene selection, we identified the biological functions that are most significantly associated ($p < .05$) with selected gene sets via Ingenuity Pathway Analysis (IPA 9.0, Ingenuity Systems, Redwood City, CA, http://www.ingenuity.com). A right-tailed Fisher's exact test was used to calculate a *p*-value, determining the probability that each biological function assigned to that gene set is due to chance alone. Gene networks were created with Ingenuity pathway designer.

2.2.11 Data analysis

Patch-clamp recordings are shown as means + SEM and were plotted with Igor Pro 5 software program (Wavemetrics). The optical density (OD) values from control and TRPM4 knockdown groups in the MTT and ALP assays are shown as means + SEM and were compared by a two-tailed, unpaired Student's *t*-test for each time point. Statistical significance was established at $p<.05$.

2.3 RESULTS

2.3.1 DFSCs express TRPM4 and differentiate into osteoblasts and adipocytes

First, we used RT-PCR analysis to determine whether DFSCs expressed the TRPM4 gene. We identified TRPM4 expression with the predicted molecular size (301 bp) but not the TRPM5 (600 bp), a closely related channel with similar function (Figure 2.1,A). We also confirmed TRPM4 expression in murine preosteoblast MC3T3-E1 cells and rat mandible and tibia bones. Both cells and bone tissues expressed the TRPM7 (422 bp), which is required for cell proliferation

and viability [8, 24]. In order to investigate whether stem cells of human origin expressed TRPM4, we performed RT-PCR with RNA extracted from hASCs. We identified similar gene expression pattern as the one observed with DFSCs (Figure 2.1,A). To demonstrate the multipotency of DFSCs, we tested their differentiation capability into osteoblasts and adipocytes determined by ARS and ORO staining at the end of 14 days (Figure 2.1,B). These stem cells were capable of differentiation into the respective cell types as indicated by extracellular matrix mineralization and lipid droplet accumulation. The adipogenic potential of hASCs is shown in Figure 2.1,B.

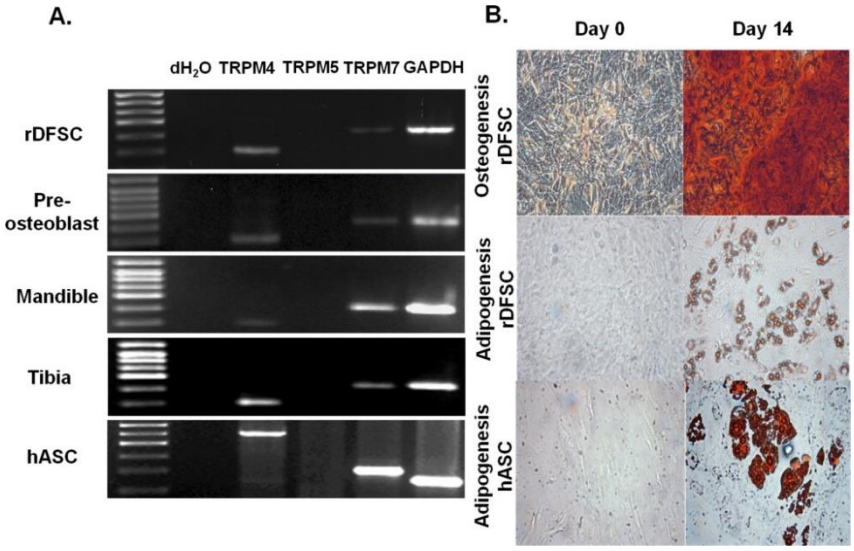

Figure 2.1 TRPM4 gene expression and multipotency of dental follicle stem cells. (A): Total RNA isolated from rat DFSCs, mandible, and tibia bones, mouse preosteoblast MC3T3-E1 cells, hASCs and reverse-transcribed into cDNA. Reverse transcriptase polymerase chain reaction was performed with specific TRPM4 and TRPM5 primers. TRPM7 and GAPDH primers served as positive controls. (B): The multipotency of DFSCs was confirmed after 14 days in osteogenic (upper panel) and adipogenic (lower panel) differentiation medium with Alizarin Red S and oil red O staining. The adipogenic potential of hASCs is also shown. Note the presence of mineralization in the extracellular matrix as well as lipid droplet accumulation at ×32 magnification. Abbreviations: GAPDH, glyceraldehyde 3-phosphate dehydrogenase; hASC, human adipocyte stem cells; rDFSC, rat dental follicle stem cells; TRPM4, transient receptor potential melastatin 4.

2.3.2 DFSCs have functional TRPM4 channels

Next, we performed electrophysiological recordings to investigate the biophysical properties of TRPM4, which is activated by increases in $[Ca^{2+}]_i$ [5]. We performed whole-cell patch-clamp recordings during perfusion of DFSCs with buffered Ca^{2+} concentrations ranging from 0.1 to 3 μM at 0 mV holding potential (Figure 2.2,A). These experiments resulted in a concentration-dependent activation of TRPM4 currents with an EC_{50} of 0.94 μM and Hill coefficient of 7.79 (Figure 2.2,C, 2.2,D). The current–voltage relationships (*I*/*V*) that are the signature of an ion channel are typical of those reported for TRPM4 (Figure 2.2,B). Perfusion of hASCs with increasing buffered Ca^{2+} concentrations (0.1–3 μM) also resulted in a concentration-dependent activation of currents and *I*/*V* similar to those described for channel (Figure 2.2,E, 2.2,F). In addition to Ca^{2+} activation, TRPM4 is voltage-dependent, where negative potentials inhibit and positive potentials increase its open probability [5, 25]. We tested the effect of −60 mV, 0 mV, and +60 mV holding potentials on TRPM4 currents with 1 μM buffered Ca^{2+}. Patch-clamp recordings at negative potentials suppressed and at positive potentials increased the current amplitude compared to 0 mV (Figure 2.3,A). The effect of voltage on TRPM4 is shown by the *I*/*V* from representative cells (Figure 2.3,B). The opening of TRPM4 results in Na^+ entry into cells and depolarization. Hence, we examined channel conductivity by replacing NaCl in the extracellular solution with choline chloride. Under this condition, inward currents were completely abolished compared to cells maintained in NaCl solution during experiments with 1 μM buffered Ca^{2+} and +60 mV holding potential (Figure 2.3,C). The replacement of

Na^+ caused a noticeable shift in the reversal potential due to hyperpolarization (Figure 2.3,D; black arrow).

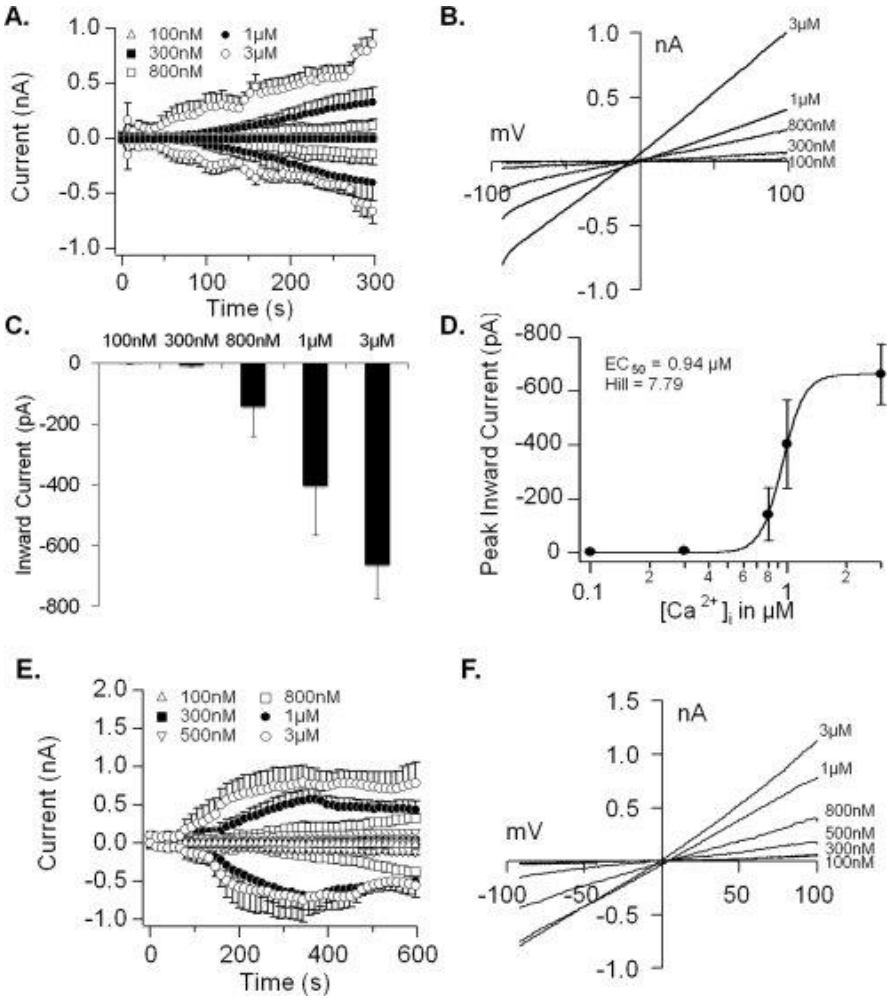

Figure 2.2 Calcium-dependent activation of transient receptor potential melastatin 4 (TRPM4) currents in dental follicle stem cells. (A): Average inward and outward currents during perfusion with increasing buffered Ca^{2+}concentrations. Traces represent the mean + SEM (*n* = 5–8 cells per concentration) recorded at 0 mV holding potential. (B): Current–voltage relationship (*I*/*V*) under experimental conditions described in (A) taken from representative cells at 300 second for each Ca^{2+} concentration. (C): Average inward currents (mean + SEM) from cells represented in panel (A). (D): A dose-response analysis revealed an EC_{50} of 0.94 µM and Hill coefficient of 7.79. (E): Average inward and outward currents during perfusion of human adipocyte stem cells with increasing buffered Ca^{2+} concentrations. Traces represent the mean + SEM (*n* = 3–6 cells per concentration) recorded at 0 mV holding potential. (F): Current–voltage relationship (*I*/*V*) under experimental conditions described in (E) taken from representative cells at 600 second for each Ca^{2+} concentration.

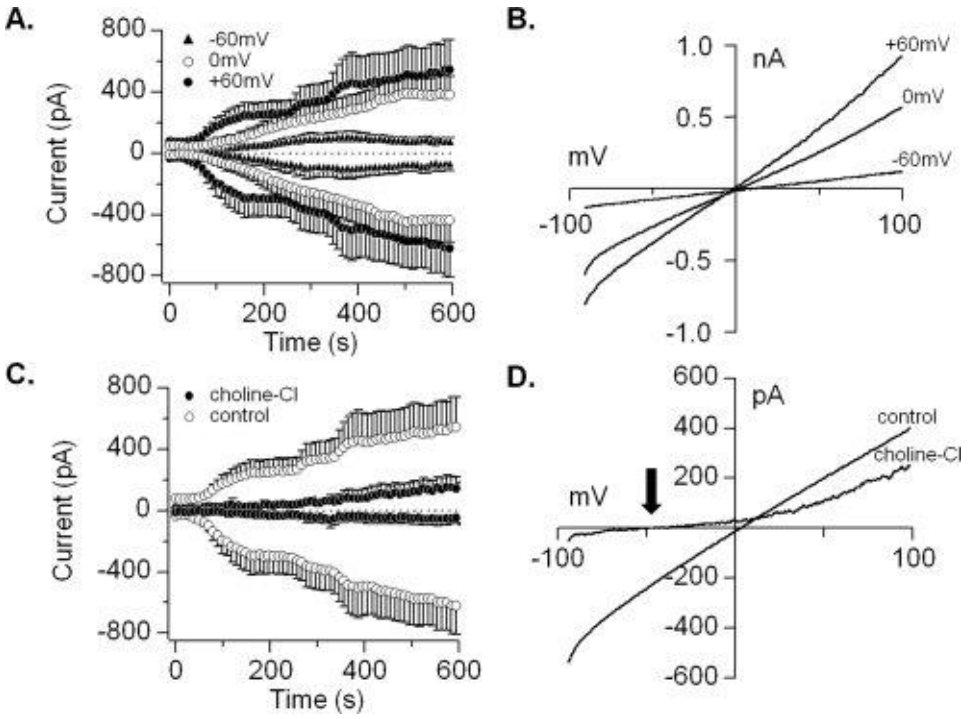

Figure 2.3 Voltage dependency and ionic conductivity of transient receptor potential melastatin 4 (TRPM4) in dental follicle stem cells (DFSCs). (A): Average inward and outward currents in response to 1 μM Ca^{2+} at +60 mV, 0 mV, and −60 mV holding potentials. Traces are mean + SEM (n = 5–6 cells per holding potential). (B): Current–voltage relationship (I/V) under experimental conditions described above at 600 s from representative cells. (C): Average inward and outward currents from DFSCs maintained in NaCl solution compared to cells kept in extracellular buffer with choline-Cl replacing NaCl. Traces are mean + SEM (n = 6–12 cells). (D): Current–voltage relationship (I/V) taken at 600 second from a representative cell. Note the shift in reversal potential (arrow) and hyperpolarization caused by the lack of Na^+ entry with choline-Cl substitution.

2.3.3 Molecular suppression of TRPM4 inhibits channel activity and cell proliferation

To investigate the functional significance of TRPM4 in DFSCs, we used shRNA and a lentiviral vector to generate stable TRPM4 knockdown cells. We confirmed the effectiveness of the shRNA by performing patch-clamp recordings with 1 μM buffered Ca^{2+} and 0 mV holding potential (HP) to activate the channel.

TRPM4 currents were significantly reduced in knockdown cells compared to control shRNA (Figure 2.4,A) and confirmed by the *I*/*V* (Figure 2.4,B). In stem cells, a decrease in cell proliferation is required prior to differentiation [26, 27]. Therefore, we used the MTT assay to examine whether cell proliferation was impacted by TRPM4 during osteogenesis and adipogenesis. Inhibition of TRPM4 significantly decreased cell proliferation compared to control shRNA cells during a 96-hour period when placed in osteogenic medium (Figure 2.4,C). Under adipogenic conditions, there was a reduction in cell proliferation only during the initial 48 hours with TRPM4 knockdown (Figure 2.4,D). Based on these results, we reasoned that if cell proliferation decreased during osteogenesis, there was a possibility that TRPM4 suppression would facilitate osteoblast but not adipocyte differentiation.

2.3.4 TRPM4 inhibits osteogenesis but facilitates adipogenesis

In order to test TRPM4's function on DFSC differentiation, we cultured cells in osteogenic and adipogenic media over 21 days and performed ARS and ORO staining on days 0, 7, 14, and 21. Inhibition of TRPM4 with two different sets of shRNAs (I and II) enhanced mineralization of DFSCs under osteogenic conditions compared to control shRNA cells, as determined by ARS staining (Figure 2.5,A). Furthermore, DFSCs cultured under adipogenic conditions failed to differentiate into adipocytes, as indicated by the absence of ORO staining (Figure 2.5,B). These results suggest that TRPM4 inhibits osteogenesis but is required for or at least facilitates adipogenesis.

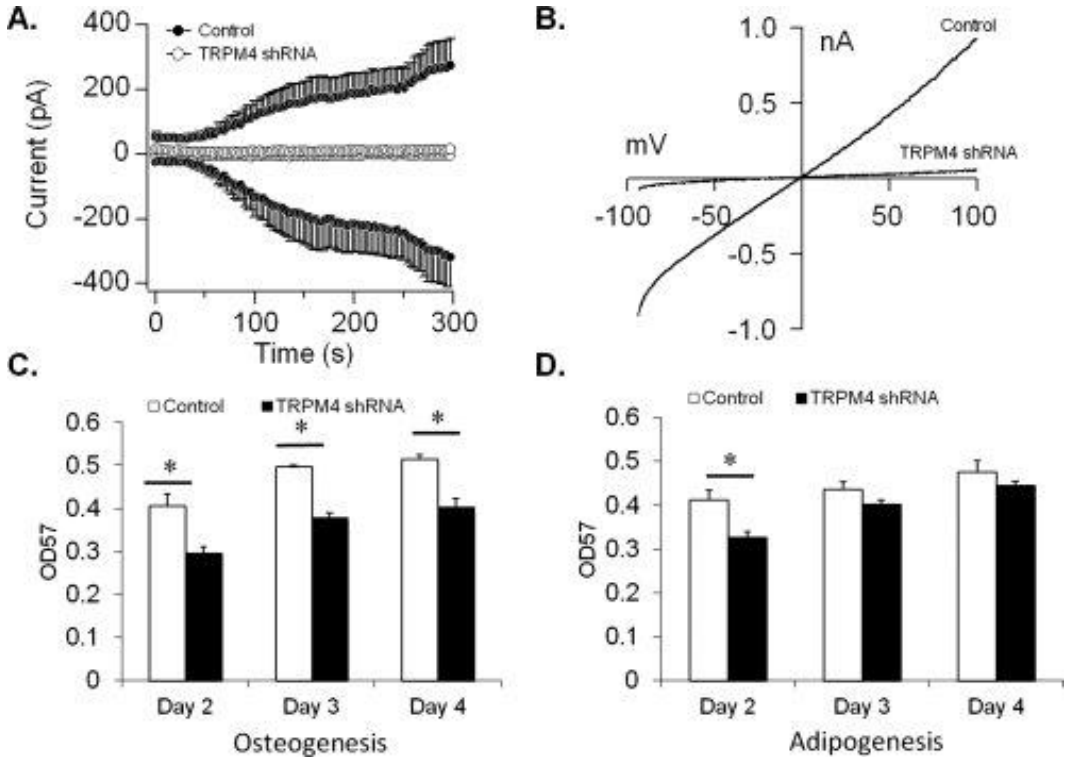

Figure 2.4 TRPM4 knockdown and its impact on cell proliferation. (A): Average inward and outward currents from control shRNA (n = 9) and TRPM4 shRNA cells (n = 6) recorded at +60 mV holding potential and 1 μM buffered Ca^{2+}. A noticeable reduction in current amplitude is seen with TRPM4 knockdown. Traces represent mean + SEM. (B): Current–voltage relationship (I/V) obtained from representative cells at 300 s. (C, D): The effect of TRPM4 knockdown on cell proliferation was examined by MTT assay. A significant decrease in cell proliferation was observed in TRPM4 shRNA cells compared to control shRNA at all time points under osteogenic but not adipogenic conditions. Data are shown as mean + S.E.M. (n = 6 wells/time point); *, $p < .05$. Abbreviations: MTT, (3-(4,5-Dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide; TRPM4, transient receptor potential melastatin 4; shRNA, short hairpin RNA.

2.3.5 TRPM4 controls Ca^{2+} signals and ALP enzyme activity

Calcium oscillations are linked to stem cell differentiation, and TRPM4 is key regulator of Ca^{2+} signaling in different cell types [7, 18, 19, 12]. Therefore, we performed real-time Ca^{2+} imaging analysis to determine its impact on Ca^{2+} signals

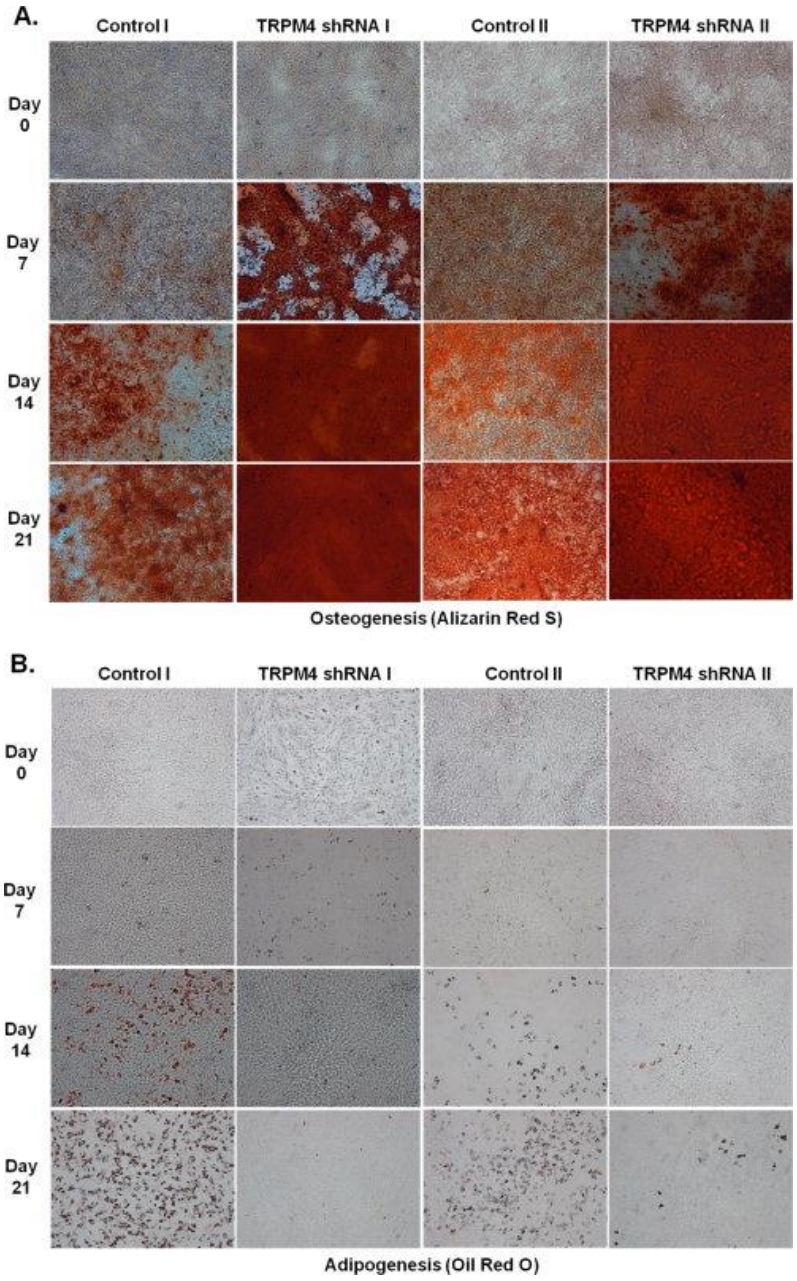

Figure 2.5 Molecular suppression of TRPM4 enhances osteogenesis but inhibits adipogenesis. (A): Extracellular matrix mineralization shown by Alizarin Red S staining during a 21-day period in control shRNA and TRPM4 shRNA cells. (B): Lipid droplet accumulation during a 21-day period in control shRNA and TRPM4 shRNA cells after Oil Red O staining. Suppression of TRPM4 enhanced mineralization during osteogenesis but inhibited lipid droplet accumulation during adipogenesis. Images are representative of three different experiments (×10 magnification). Abbreviations: TRPM4, transient receptor potential melastatin 4; shRNA, short hairpin RNA.

generated by ATP, which influence stem cell differentiation [28, 29]. Stimulation of control shRNA cells with 100 μM ATP resulted in the typical increase in $[Ca^{2+}]_i$ characterized by a first phase due to Ca^{2+} release from the ER, followed by a secondary phase due to Ca^{2+} influx via SOCs (Figure 2.6,A). TRPM4 knockdown transformed the biphasic Ca^{2+} pattern into a gradual and sustained increase (Figure 2.6,B). The average responses of cells from three different cell passages are shown in Figure 2.6,C. The proliferation and osteogenic differentiation assays combined with the Ca^{2+} signaling data prompted us to investigate whether enhanced osteoblast differentiation and mineralization in knockdown cells were associated with an increase in ALP enzyme activity. This enzyme is one of the hallmarks for osteogenesis [30]. We found that there was also a significant increase in ALP enzyme activity on days 14 and 21 of osteoblast differentiation compared to control shRNA cells (Figure 2.6,D).

2.3.6 Genes regulated by TRPM4 during osteogenic and adipogenic differentiation

Finally, we used whole genome microarray analysis to investigate potential genes controlled by TRPM4 during 14 days of differentiation. Based on the approach described for microarray analysis, we first examined genes involved in osteogenesis because of the enhancement of mineralization and osteoblast formation with TRPM4 knockdown. We identified four genes involved in bone mineralization (nuclear factor erythroid-derived 2 [NFE2], asporin [ASPN], matrix extracellular phosphoglycoprotein [MEPE], and matrix γ-carboxyglutamate protein [MGP]). All four genes were upregulated (MEPE 11-fold; MGP 8.6-fold; NFE2 1.9-fold) compared to control shRNA cells, while ASPN gene expression was 37.4-

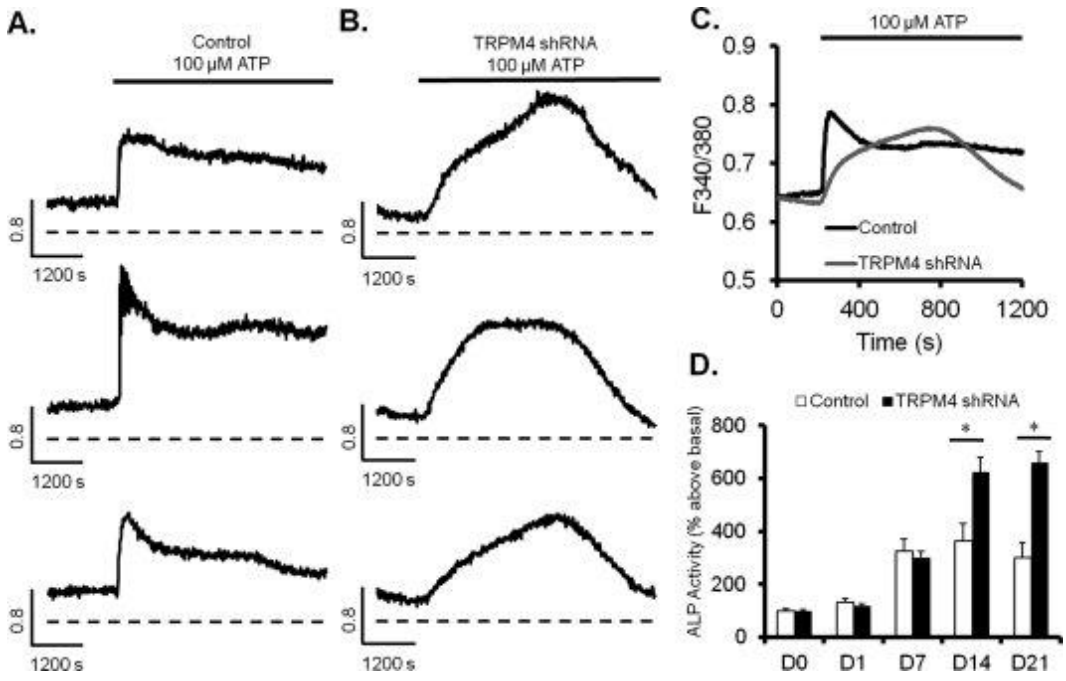

Figure 2.6 TRPM4 regulates Ca^{2+} signals and increases ALP enzyme activity. (A): Calcium signals from single control shRNA cells in response to 100 µM ATP. (B): Same experiment as in (A), except with TRPM4 shRNA cells. (C): Average Ca^{2+} signals from control shRNA (n = 47 cells) and TRPM4 knockdown (n = 64 cells) from three different experiments. (D): ALP enzyme activity during a 21-day period under osteogenic differentiation conditions. Results are presented as mean + SEM from three different experiments (n = 4 wells per time point); *, p < .05. Abbreviations: ALP, alkaline phosphatase; TRPM4, transient receptor potential melastatin 4; shRNA, short hairpin RNA.

fold higher in controls than knockdown cells (Figure 2.7,A). We also identified four genes involved in osteoblast differentiation (Cbp/p300-interacting transactivator 1 [CITED1], cyclin-dependent kinase 6 [CDK6], c-fos induced growth factor [FIGF], and IL 6 receptor [IL6R]). Both CITED1 and CDK6 genes were downregulated 1.5- and 0.9-fold in controls compared to TRPM4 shRNA cells, whereas FIGF and IL6 were upregulated twofold and 0.7-fold, respectively (Figure 2.7,A). In addition, we found the bone development gene, Lumican (LUM), upregulated 12.6-fold with TRPM4 suppression. Furthermore, our results indicated that TRPM4 knockdown inhibited adipogenesis. We identified eight genes: Lipin 1 (LPIN1), tribbles

homolog 3 (TRIB3), WNT inhibitory factor 1 (WIF1), secreted frizzled-related protein 1 (SFRP1), matrix metallopeptidase 3 (MMP3), selenium binding protein 1 (SELENBP1), aldehyde dehydrogenase 6 family member A1 (ALDH6A1), and regulator of G-protein signaling 2 (RGS2) involved in this process (Figure 2.7,B). Of the eight, the TRIB3 was the only gene downregulated, with a 24.7-fold reduction in knockdown compared to control cells. From the upregulated genes, SFRP1 (10.8-fold) and RGS2 (onefold) expression were higher in control cells. TRPM4 suppression increased LPIN1 (3.7-fold), WIF1 (1.3-fold), MMP3 (22.9-fold), SELENBP1 (3.2-fold), and ALDH6A1 (1.4-fold) over control cells. The genes involved in brown fat differentiation are shown in the diagram (Figure 2.7,B).

2.4 DISCUSSION

The study describes for the first time the expression and functions of TRPM4 in stem cells. Using rat DFSCs, we identified TRPM4 gene expression and currents typical for the channel, which were Ca^{2+}-dependent, voltage sensitive, and conducted mainly Na^{+}. Perfusion of cells with increasing Ca^{2+} concentrations resulted in the activation of TRPM4 with an EC_{50} of 0.94 μM and Hill coefficient of 7.79. This is consistent with previous findings in pancreatic α and β cells [19]; thus it appears that in DFSCs, TRPM4 is more sensitive to changes in $[Ca^{2+}]_i$. The TRPM4 channel also exhibited a strong voltage dependency with currents suppressed at negative and facilitated at positive holding potentials [5, 25]. These currents were mainly due to Na^{+} entry into cells, as prior to performing functional studies. Under both conditions, we were able to identify mineralization and lipid droplet accumulation after 14 days.

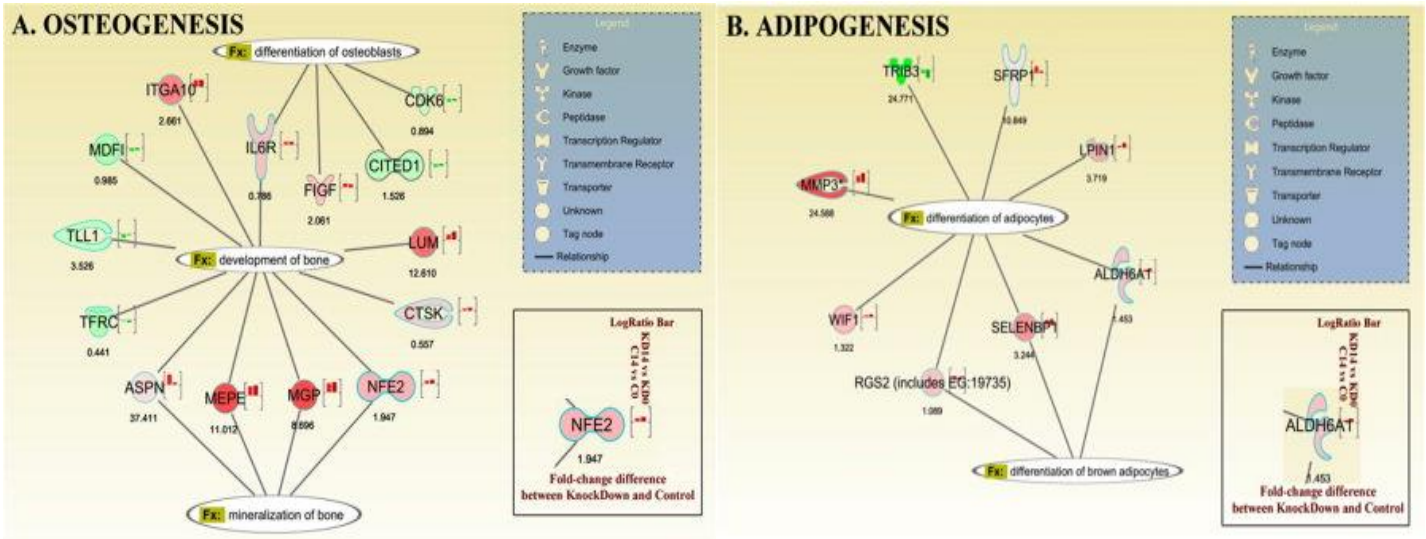

Figure 2.7 Whole genome microarray analysis of osteogenic and adipogenic genes impacted by transient receptor potential melastatin 4 (TRPM4). **(A):** Gene expression related to osteoblast differentiation, bone development and mineralization in TRPM4 shRNA cells after 14 days in osteogenic conditions. **(B):** Gene expression related to adipocyte differentiation from TRPM4 shRNA cells after 14 days in adipogenic conditions. RNA was extracted from control shRNA [C] and TRPM4 knockdown cells [KD] prior to differentiation induction [C0 and KD0] and after 2 weeks of differentiation [C14 and KD14]. The values under each gene represent the difference in fold change between C14 and KD14 groups. Red/green color indicates upregulation/downregulation during differentiation in control (left bars) and knockdown cells (right bars). The biological functions shown in the diagrams have $p < .05$. Abbreviations: ALDH6A1, aldehyde dehydrogenase 6 family member A1; ASPN, asporin; CDK6, cyclin-dependent kinase 6; CITED1, Cbp/p300-interacting transactivator 1; CTSK, cathepsin K; FIGF, c-fos induced growth factor; IL6R, interleukin 6 receptor; ITGA10, integrin alpha-10; LUM, Lumican; LPIN1, Lipin 1; MDFI, myoD family inhibitor; MGP, matrix γ-carboxyglutamate protein; MEPE, matrix extracellular phosphoglycoprotein; MMP3, matrix metallopeptidase 3; NFE2, Nuclear factor erythroid-derived 2; RGS2, regulator of G-protein signaling 2; SFRP1, secreted frizzled-related protein 1; SELENBP1, selenium binding protein 1; TRIB3, tribbles homolog 3; TFRC, transferrin receptor protein 1; TLL1, tolloid-like 1; WIF1, WNT inhibitory factor 1; shRNA, short hairpin RNA.

To investigate the role of TRPM4 in DFSC differentiation, we generated stable knockdown cells with shRNA and a lentiviral vector. We selected this approach because of concern over loss of knockdown effect with transient transfection during differentiation. Inhibition of TRPM4 was confirmed with elevated Ca^{2+} concentration and+60 mV holding potential that resulted in a significant reduction in current amplitude. In DFSCs, inhibition of TRPM4 did not cause cell death, which is similar to findings in knockout mice [31, 32], suggesting that TRPM4 is not lethal. With the availability of the knockdown cells, we examined TRPM4's impact on proliferation and differentiation. A decrease in stem cell proliferation is a prerequisite for osteogenesis and adipogenesis [26, 27]. The fact that TRPM4 suppression decreased DFSCs proliferation during the initial 96 hours of osteogenesis, but not of adipogenesis, indicated a possible enhancement of osteoblast differentiation. This hypothesis was supported by the increased mineralization and ALP enzyme activity; however, under adipogenic conditions, DFSCs failed to differentiate into adipocytes. These findings suggest that TRPM4 functions as an inhibitor of osteogenesis, while it is required and/or facilitates adipogenesis.

Calcium oscillations are often present during stem cell differentiation and are linked to the differentiation process by activating specific transcription factors [12, 13]. To provide insights into the mechanism controlling DFSC differentiation, we investigated their Ca^{2+} signaling pattern of DFSCs during agonist stimulation. Inhibition of TRPM4 transformed the normal ATP-induced biphasic Ca^{2+} pattern, characterized by a sharp increase (ER release–first phase) followed by influx

(Ca^{2+} entry via SOCs–secondary phase) and then a gradual increase followed by a sharp decrease. This was unexpected and different from observations in T lymphocytes, which also use SOCs as the main Ca^{2+} entry pathway. TRPM4 suppression in immune cells results in a sustained secondary phase without impacting the first phase and increases IL-2 production via the calcineurin-NFAT pathway [7, 11]. It is possible that in DFSCs there could be direct interaction between TRPM4 and the ER to control the rate of Ca^{2+} release and refill. Such relationship between ER proteins (e.g., stromal interaction molecule 1) and ion channels (e.g., SOCs) are essential for Ca^{2+} signaling in nonexcitable cells [33, 34]. Another possibility is that of TRPM4 multimerization with SOCs to control the rate of Ca^{2+} influx. Several TRP members are capable of homomultimerization and heteromultimerization [35–38]. However, the gradual increase in $[Ca^{2+}]_i$ with TRPM4 suppression suggests a regulatory mechanism between TRPM4 and the ER. Further studies will be required to elucidate the mechanism underlying the control of Ca^{2+} signals by TRPM4 in DFSCs.

Functional studies in different cell types provide a direct link between TRPM4, Ca^{2+} signaling, and cellular responses. Together, they control dendritic cell migration and cytokine production in T lymphocytes [7, 11, 21]. They also regulate insulin and glucagon secretion from pancreatic islet cells and myogenic constriction in cerebral arteries [18–20]. Because gene transcription is one of the downstream events regulated by TRPM4, we performed whole genome microarray analysis to identify potential genes responsible for the enhancement of osteogenesis and inhibition of adipogenesis. We identified four genes involved in osteoblast

differentiation (CITED1, CDK6, FIGF, IL6R) and four in bone mineralization (NFE2, ASPN, MEPE, MGP). Comparison between osteogenic differentiation genes from control and knockdown cells revealed a maximum of twofold differences, whereas for bone mineralization, the MEPE and MGP genes were upregulated 11- and 8.6-fold with TRPM4 suppression. These findings are consistent with studies in human dental pulp and murine preosteoblast cells, where MEPE expression enhances osteoblast differentiation and mineralization via the BMP-2 signaling pathway [39, 40]. Although the role of MGP in dental tissue is unclear, studies in knockout mice show increased mineralization of pulmonary and renal arteries via the BMP-4 pathway [41]. This is contrary to our observation in DFSCs. Perhaps the differences in signaling pathway and tissues affected by MGP expression could account for this disparity. In fact, the BMP-2 pathway is reported to control DFSC differentiation into osteoblasts [42]. Furthermore, TRPM4 knockdown inhibited ASPN expression 39.4-fold over control cells. This is relevant to DFSCs because this gene is predominantly expressed in the PDL and in dental follicle cells that give rise to the ligament [43]. Since ASPN expression inhibits differentiation and mineralization of the PDL [43], its suppression by TRPM4 knockdown may have contributed to the enhanced osteogenesis. Interestingly, we found the LUM gene upregulated 12.6-fold over control cells. Its roles in collagen formation, epithelial cell migration, and tissue repair suggest a possible role for TRPM4 on bone development [44, 45].

When TRPM4 knockdown cells were placed in adipogenic medium, they failed to differentiate into adipocytes. Of the genes related to this process, the TRB3

was downregulated 24.7-fold compared to control cells. This finding is consistent with reports in type 2 diabetic rats, where silencing of the TRB3 decreases adipocyte formation [46]. Two other notable genes, SFRP1 and MMP3, were upregulated in both groups. TRPM4 knockdown inhibited SFRP1 expression 10.8-fold compared to control cells, and SFRP1 is reported to be a regulator of the Wnt/β-catenin pathway. Its expression enhances adipocyte differentiation in humans and mice [47]. The analysis also revealed a 22.9-fold increase in MMP3 expression compared to control cells. The knockout of this gene also enhances adipogenesis during mammary gland involution in mice, along with adipocyte hypertrophy [48]. The effects of TRPM4 knockdown on the TRB3, SFRP1, and MMP3 genes are expected to inhibit adipocyte differentiation based on their roles during adipogenesis.

Conclusion

TRPM4 is a CAN channel present in DFSCs. These stem cells not only express the TRPM4 gene but also have currents typical for the channel. Functional experiments suggested that TRPM4 acts as an inhibitor of osteogenesis, since channel suppression increased mineralization and ALP enzyme activity. However, it appears to be required and/or facilitates adipogenesis due to the absence of adipocyte differentiation in TRPM4 knockdown cells. The effect of TRPM4 on osteogenesis and adipogenesis seems to be linked to the Ca^{2+} signals, which could be a key factor controlling expression of certain genes.

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CHAPTER 3: HISTAMINE-INDUCED Ca^{2+} SIGNALLING IS MEDIATED BY TRPM4 CHANNELS IN HUMAN ADIPOSE-DERIVED STEM CELLS*

3.1 INTRODUCTION

Transient receptor potential channels (TRPs) are a family of proteins originally identified in the *Drosophila melanogaster* visual system and have important roles in cellular function. All TRPs include six transmembrane segments with the pore region between segments 5 and 6 and intracellular N- and C-termini. They are divided into the following six subfamilies: TRPC (canonical), TRPV (vanilloid), TRPM (melastatin), TRPP (polycystin), TRPML (mucolipin) and TRPA (ankyrin) [1]. TRPM4 belongs to the melastatin subfamily, and TRPM4 and TRPM5 are the only Ca^{2+}-activated channels [2, 3]. Although not permeable to Ca^{2+}, TRPM4 is proposed to facilitate voltage-dependent Ca^{2+} channel (VDCC) activation in excitable cells and to decrease the driving force for Ca^{2+} influx via store-operated Ca^{2+} channels (SOCs) in non-excitable cells by depolarization [2, 4, 5]. Recently, we have reported that molecular inhibition of TRPM4 inhibits adipogenesis in rat dental follicle stem cells (rDFSCs), which suggests that the channel is required for adipocyte differentiation [6]. This regulatory mechanism is mediated via Ca^{2+} signalling and the expression of specific adipogenic genes. In rDFSCs, inhibition of TRPM4 transforms the primary and secondary phases of the Ca^{2+} signals into a gradual and sustained increase that is similar to the one observed

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in non-excitable cells (e.g. immune cells) that utilizes SOCs as the main pathway for Ca^{2+} influx [7, 8]. The opposite phenomenon occurs in excitable cells (e.g. pancreatic α- and β-cells and dendrite), where TRPM4 suppression decreases the magnitude of the Ca^{2+} signals due to a reduction in VDCC channel activity [5, 9, 10].

Ionized Ca^{2+} is a well-known second messenger controlling basically every cellular process. Elevations in $[Ca^{2+}]_i$ are observed frequently in response to hormone and growth factor stimulation as well as spontaneous increases. These Ca^{2+} signals are often due to influx from the extracellular space and release from intracellular stores. In stem cells, SOCs were first reported by Kawano et al. [53]. It was shown that Ca^{2+} influx contributes to the signals that co-ordinate cell proliferation and differentiation. In addition, Ca^{2+} oscillations are important for specificity and effectiveness of gene expression, for example nuclear factor of activated T-cells (NFAT) transcription activity [11]. This is supported by the fact that NFAT translocation into the nucleus is needed for stem cell differentiation, but halts at the terminal stages of adipogenesis and osteogenesis [12, 13]. An increase in Ca^{2+} influx in mesenchymal stem cells accelerates osteogenic differentiation via the mitogen-activated protein kinase (MAPK) pathway [13]. Ca^{2+} signalling is also required for embryonic and mesenchymal stem cell cycle progression through G_1/S-phase by inducing expression of c-*myc*, a key gene for self-renewal and pluripotency [14–16]. Furthermore, increases in $[Ca^{2+}]_i$ up-regulate peroxisome-proliferator-activated receptor γ (PPARγ) gene expression, a critical transcription factor for adipocyte differentiation [17].

Ion channels are important regulators of cell proliferation and differentiation due to their ability to conduct Ca^{2+} directly into cells or indirectly by controlling the opening and closure of Ca^{2+} channels. In the first report of TRPM4 in stem cells, we have determined that the channel is required for adipocyte differentiation in rDFSCs by controlling Ca^{2+} signals and adipocyte-specific genes [6]. There are no reports of TRPM4 in any other type of stem cell. However, members of the TRP family such as the TRPM7 are required for bone marrow stem cell proliferation and viability [18]. The channel is also important for early embryonic development [19]. TRPM2 enhances mesenchymal stem cell proliferation [20]. Among non-TRPs, the delayed rectifier K^+ and Ca^{2+}-activated K^+ channels are required for mesenchymal stem cell proliferation [21–23]. In human adipose-derived stem cells (hASCs), the delayed rectifier K^+, Ca^{2+}-activated K^+, transient outward K^+ and tetrodotoxin (TTX)-sensitive transient inward Na^+ channels are present, although their roles in differentiation remain unknown [24]. Despite the lack of information on TRPs during hASC differentiation, some control the functioning of pre-adipocyte and adipocyte cells. TRPC1 and TRPC5 are responsible for constitutive Ca^{2+} influx in differentiated 3T3-L1 cells and adipose tissues [25]. Expression of TRPV1 diminishes during adipogenesis in obese humans and mice [26], and channel activation results in Ca^{2+} influx and uncoupling of protein 1-dependent thermogenesis [27]. Nevertheless, TRPV1-null mice fail to become obese on a high-fat diet because of increased thermogenic activity [28]. Recently, TRPM8 was shown to stimulate uncoupling protein 1-dependent thermogenesis and prevent obesity in mice [29]. Because of TRPM4's

ability to control Ca^{2+} signalling in other cell types and its requirement for adipogenesis in rDFSCs, we have examined its impact on Ca^{2+} signals and adipocyte differentiation in hASCs, which is a more suitable stem cell type for adipogenic studies [30].

3.2 MATERIALS AND METHODS

3.2.1 Reagents

All reagents were purchased from Sigma–Aldrich, except for fura 2 acetoxymethyl ester (fura 2/AM), which was from Molecular Probes, and D-calcium pantothenate, which was from Acros Organics.

3.2.2 Cell culture

hASCs were isolated from lipoaspirates of abdomen and breast adipose tissues according to [31]. The multi-potency of this stem cell type has been confirmed by different laboratories [32–36]. Tissues were donated by one consenting Caucasian female and one consenting Caucasian male, aged 34 and 55 years respectively, body mass index (BMI) from 28.2 to 33.78, under a protocol reviewed and approved by the Pennington Biomedical Institutional Review Board (#PBRC23040) and maintained in Dulbecco's modified Eagle's medium (DMEM)/Ham's F-12 medium with 10% FBS (Atlanta Biologicals) and aerated with 5% CO_2 at 37°C. All experiments were performed with cells from passages 3 to 8.

3.2.3 Induction and detection of adipogenesis

Cells reaching between 80% and 90% confluence were induced with differentiation medium containing DMEM/Ham's F-12 supplemented with 3%

FBS, 0.25 mM 3-isobutyl-1-methylxanthine (IBMX), 33 μM biotin, 17 μM D-calcium pantothenate and 100 nM human insulin for 3 days. Adipocyte medium having the same composition as differentiation medium except for IBMX and rosiglitazone (5 μM) was changed every 3 days from day 3 to day 21 [37]. Adipogenesis was determined by Oil Red O staining. Briefly, cells were washed with PBS, fixed with 10% formalin for 10 min, washed twice with distilled water and incubated with 60% propan-2-ol for 5 min. Cells were then stained with Oil Red O solution for 5 min and washed again to remove excess dye. The presence of lipid droplets was visualized by phase-contrast microscopy using an inverted microscope (Zeiss). Adipocyte cell count was performed with Image-Pro® Analyzer 7.0 (Media Cybernetics).

3.2.4 RT-PCR

Total RNA was extracted from hASCs using the RNAqueous-4PCR® kit according to the manufacturer's instructions (Ambion). The RNA was purified using DNase I treatment. Reverse transcription (RT) and PCR were performed using the RETROscript® kit (Ambion). Total RNA was extracted from abdominal adipose tissue from three females, ages 40–60 years, BMI from 27 to 30, according to an approved protocol by Institutional Review Board of the University of Florida using TRIzol® reagent (Invitrogen). Briefly, 300 mg of human adipose tissue was placed in a mortar pre-chilled with liquid nitrogen. A pestle was used to homogenize the deep frozen tissue with the presence of liquid nitrogen throughout the process. To the sample, 1 ml of TRIzol® was added, and the mixture was transferred to a 1.5 ml Eppendorf tube. After 5 min of incubation at room

temperature, 100 µl of chloroform was added to the mixture, vortex-mixed vigorously for 15 s and kept at room temperature for another 10 min. The mixture was phase-separated by centrifugation at 12000 ***g*** for 15 min at 4°C. Following centrifugation, the mixture was kept at 4°C for 30 min to let the fat solidify. After careful removal of the upper layer of fat, the middle aqueous phase was transferred into a new tube. To precipitate the RNA, 500 µl of propan-2-ol was added. After 10 min of incubation at room temperature, precipitated RNA was pelleted by centrifugation at 12000 ***g*** for 10 min at 4°C. The pellet was then washed with 75% ethanol. After briefly air-drying the RNA pellet, 50 µl of RNase-free water was added to dissolve the RNA and the concentration was determined by measuring the A_{260}/A_{280} ratio. Transcriptor first- strand cDNA synthesis kit was purchased from Roche. Random primer and 4 µg of total RNA were used to generate cDNA. The primers used are listed in Table 3.1.

Table 3.1 List of primers of ion channel genes for RT-PCR

Gene	Forward primer (5'-3')	Reverse primer (5'-3')	Size (bp)
TRPM4 (for hASCs)	AGCATGGTGCCGGAGAA	GGTGTCTCTATTCCGGACCACA	600
TRPM4 (for human adipose tissue)	CCTCTTTGGCGAGTGCTATC	CAAAAGAAGGCGAGAACCAG	222
TRPM5	CAGAACATCACCTCACACCAG	GGTTCTCGCTCTTCTGGTTC	640
TRPM6	CCAGAGCCAGGAGAAAACAG	AAAGGGGAACTCTCCTCCAA	419
TRPM7	TGAAACGAGTGAGTTCTCTTGCTG	CACAGGTGTAAATGGAATGCTC	309
Cav1.1	AACGCCAAGAGGAGTATTATG	ATGGCTGTTGCTATGGTTGC	425
Cav1.2	CTGGACAAGAACCAGCGACAGTGCG	ATCACGATCAGGAGGGCCACATAGGG	562

(Table 3.1 continued)

Gene	Forward primer (5'-3')	Reverse primer (5'-3')	Size (bp)
Cav1.3	TATGTGGCCCTCCTCATAGC	CTCAGGGTCACAGAGCTTCC	219
Cav1.4	GGACCATGGCCCCATCTATAATTACCG	CCTGAAGAGCCACCTTGCCGAAC	764
GAPDH	AACAGCGACACCCACTCCTC	GGAGGGGAGATTCAGTGTGGT	258

GAPDH, glyceraldehyde-3-phosphate dehydrogenase.

3.2.5 Quantitative RT–PCR

From each sample, 2 μg of total RNA was reverse-transcribed into 20 μl of cDNA. Each PCR was prepared by mixing 2 μl of the cDNA with 2× SYBR Green PCR master mix (Life Technologies) and gene-specific primers (Table 3.2). The PCR was carried out with ABI 7300 real-time PCR system (Life Technologies) to obtain the C_T value. Relative gene expression (RGE) was calculated by the ΔC_T method using β-actin as the endogenous control for normalization and Cyclophilin B as the reference control with an RGE of 1.

Table 3.2 List of primers of adipogenic marker genes for quantitative RT-PCR

Gene	Forward primer (5'-3')	Reverse primer (5'-3')	Size (bp)
C/EBPα	CGGTGGACAAGAACAGCAAC	CGGAATCTCCTAGTCCTGGC	365
C/EBPβ	CACAGCGACGACTGCAAGATCC	CTTGAACAAGTTCCGCAGGGTG	188
PPARγ2	GCTGTTATGGGTGAAACTCTG	ATAAGGTGGAGATGCAGGTTC	325
aP2	TGGTTGATTTTCCATCCCAT	TACTGGGCCAGGAATTTGAT	150
Adiponectin	GGCCGTGATGGCAGAGAT	TTTCACCGATGTCTCCCTTAGG	88
Cyclophilin B	GGAGATGGCACAGGAGGAAA	CGTAGTGCTTCAGTTTGAAGTTCTCA	72

3.2.6 Western blot analysis

hASCs from two different lines were grown to confluency and collected into protein lysis buffer with the addition of protease inhibitor cocktail. Protein concentration was determined by the Bradford method. BSA protein standard was purchased from Bio-Rad Laboratories. Then, 50 μg of protein was separated by SDS/8% PAGE. Proteins were transferred on to a nitrocellulose membrane and subjected to sequential Western blotting analysis with anti-TRPM4 (1:300) antibody (Alomone Labs) overnight at 4°C and visualized by ECL Prime Western Blotting Detection Reagent (GE Healthcare Life Sciences) followed by anti-$Ca_v1.2$ (1:300) antibody (Alomone Labs) without stripping off the membrane.

3.2.7 Generation of stable TRPM4 knockdown cells

hASCs were transduced with lentivirus plasmids (Sigma–Aldrich) in a pLKO.1 backbone containing either non-specific control (SHC002) or shRNAs specific for human TRPM4 (TRCN0000044924 and TRCN0000044926) under the control of the U6 promoter, with the puromycin-resistance gene and a *GFP* gene. Cells were selected in puromycin and used for electrophysiology, Ca^{2+} imaging analysis and adipogenic differentiation experiments.

3.2.8 Electrophysiology

Cells were maintained in standard modified Ringer's solution of the following composition: 140 mM NaCl, 2.8 mM KCl, 1 mM $CaCl_2$, 2 mM $MgCl_2$, 4 mM glucose and 10 mM Hepes/NaOH (pH 7.2). Replacement of extracellular Na^+ was accomplished by 140 mM *N*-methyl-D-glucamine (NMDG). The internal solution contained 120 mM caesium glutamate, 8 mM NaCl, 1 mM $MgCl_2$, 10 mM

caesium 1,2-bis-(*o*-aminophenoxy) ethane-*N*,*N*,*N*',*N*'-tetra-acetic acid (BAPTA), 10 mM Hepes/CsOH (pH 7.2). The internal solution's buffered Ca^{2+} concentration was adjusted as necessary with $CaCl_2$. The osmolarity of the solutions was ~300 mOsm/l. TRPM4 currents were recorded in the tight-seal whole-cell configuration mode at 21–25°C. High-resolution current recordings were acquired by a computer-based patch-clamp amplifier system (EPC-10, HEKA). Patch pipettes had resistances between 4 and 7 mΩ and were coated with Sigmacote silicon solution (Sigma–Aldrich). Immediately following establishment of the whole-cell configuration, voltage ramps of 50-ms duration spanning the voltage range of −100 to +100 mV were delivered from a holding potential of 0 mV at a rate of 0.5 Hz over a period of 300 s. All voltages were corrected for a liquid junction potential of 10 mV between external and internal solutions and calculated using Igor PPT Liquid Junction Potential software (Wavemetrics).

3.2.9 Calcium imaging analysis

Cells were loaded with 2 μM fura 2/AM for 30 min at 37°C. The imaging buffer containing 136 mM NaCl, 4.8 mM KCl, 1.2 mM $CaCl_2$, 1.2 mM $MgSO_4$, 10 mM Hepes, 4 mM glucose and 0.1% BSA (pH 7.3) was used for fura 2/AM loading and perfusion throughout the experiments. Calcium measurements were obtained using a dual-excitation fluorimetric imaging system (TILL-Photonics) controlled by TILLvisION software. Fura 2/AM loaded cells in a perfusion chamber were excited at 340- and 380-nm wavelengths. Fluorescence emissions were sampled at a frequency of 1 Hz and computed into relative ratio units of the

fluorescence intensity of the difference of wavelengths (F_{340}/F_{380}). Data were expressed as averages from several cells from three separate experiments.

3.2.10 Data analysis

Patch-clamp recordings, peak Ca^{2+} signals and adipocyte counts are shown as means±S.E.M. and were analysed using a two-tailed and unpaired Student's *t* test (GraphPad Software). Statistical significance was established at $P<0.05$.

3.3 RESULTS

3.3.1 TRPM4 expression in hASCs and human adipose tissue

Using RT–PCR, we have detected TRPM4 transcripts in hASCs and human adipose tissue, but not TRPM5, a related channel with similar function. In addition, we have identified *TRPM6* and *TRPM7* gene expression in stem cells and differentiated adipocytes (Figure 3.1,A). The presence of TRPM4 protein in hASCs was confirmed in two different cell lines by Western blot analysis (Figure 3.1,B).

3.3.2 Biophysical characterization of TRPM4 in hASCs

Since hASCs expressed the *TRPM4* gene, we have performed patch-clamp recordings in the whole-cell configuration mode to determine whether the channel was functionally active. On the basis of the Ca^{2+}-activated property of TRPM4, we have perfused a single hASC with intracellular buffered Ca^{2+} concentration ranging from 0.1 to 3 μM. As a result, currents with the characteristics of those previously described [2, 7] developed in a concentration-dependent manner with peak amplitude at 3 μM (Figures 3.1,C and 3.1,D). The current–voltage (*I–V*) relationship taken from representative cells at 300 s into the recording for each Ca^{2+}

concentration is shown in Figure 3.1,E. The calculated EC_{50} was 0.9 µM and the Hill coefficient was 9.09 (Figure 3.1,F). Another property of TRPM4 is the voltage-

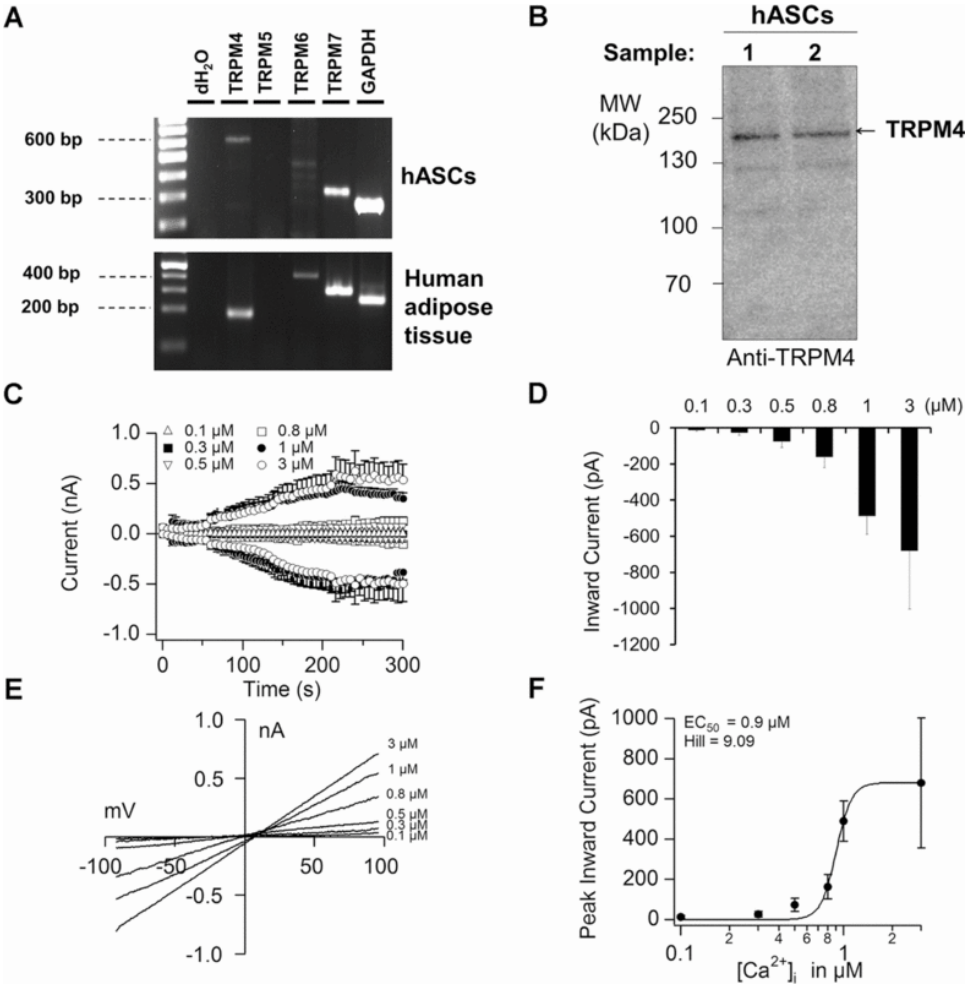

Figure 3.1 TRPM4 expression and functionality in hASCs. (A) Expression of the TRPM4 gene in hASCs and human adipose tissue. In addition, we have detected the presence of TRPM6 and TRPM7. RT–PCR was performed with specific TRPM4, TRPM5, TRPM6 and TRPM7 primers. Distilled water and glyceraldehyde-3-phosphate dehydrogenase (GAPDH) served as negative and positive controls respectively. (B) Western blot analysis confirmed the presence of TRPM4 protein in two different hASC lines. (C) Increases in the intracellular Ca^{2+} activated TRPM4 currents in a concentration-dependent manner. Average inward and outward currents during perfusion of single cells with increasing intracellular buffered Ca^{2+} concentrations. Traces represent the means±S.E.M. (n=5–10 cells per concentration) extracted at −80 mV and +80 mV from a holding potential of 0 mV. (D) Average peak inward currents from cells represented in (C). (E) *I–V* relationship under experimental conditions described in (C) taken from representative cells at 300 s into the recordings. (F) The calculated EC_{50} value and Hill coefficient for different Ca^{2+} concentrations.

dependency, where positive potentials increase its open probability and negative potentials decreases it [2]. Hence, we have performed patch-clamp recordings with holding potentials from −80 mV to +60 mV while perfusing cells with 1 μM intracellular buffered Ca^{2+} concentration. Under these conditions, we have obtained the greatest current amplitude at +60 mV and the smallest at −80 mV (Figure 3.2,A). The *I–V* relationship obtained from representative cells at 300 s is shown in Figure 3.2,B. To investigate TRPM4's ionic conductivity, we have replaced NaCl in the extracellular solution with an equimolar concentration of NMDG and performed recordings with 1 μM intracellular buffered Ca^{2+} concentration at +60 mV holding potential, which gave the maximum current amplitude. Replacement of Na^+ from the extracellular solution abolished TRPM4 currents compared with cells maintained under Na^+ containing buffer, even under high Ca^{2+} and positive holding potential conditions (Figure 3.2,C). The *I–V* relationship confirmed the lack of channel activity in the absence of Na^+ (Figure 3.2,D).

3.3.3 Inhibition of TRPM4 activity by 9-phenanthrol

Next, we have performed patch-clamp recordings using the specific TRPM4 blocker 9-phenanthrol [38–40] to further confirm its presence in hASCs. Pre-treatment of cells with 0.3–10 nM 9-phenanthrol inhibited TRPM4 currents in a concentration-dependent manner during perfusion with 1 μM intracellular buffered Ca^{2+} concentration and 0 mV holding potential (Figures 3.3,A and 3.3,B). The *I–V* relationship showed the reduction in TRPM4 activity with increased 9-phenanthrol concentration (Figure 3.3,C). The calculated IC_{50} and Hill coefficient in hASCs were 1.75 nM and 1.61 respectively (Figure 3.3,D).

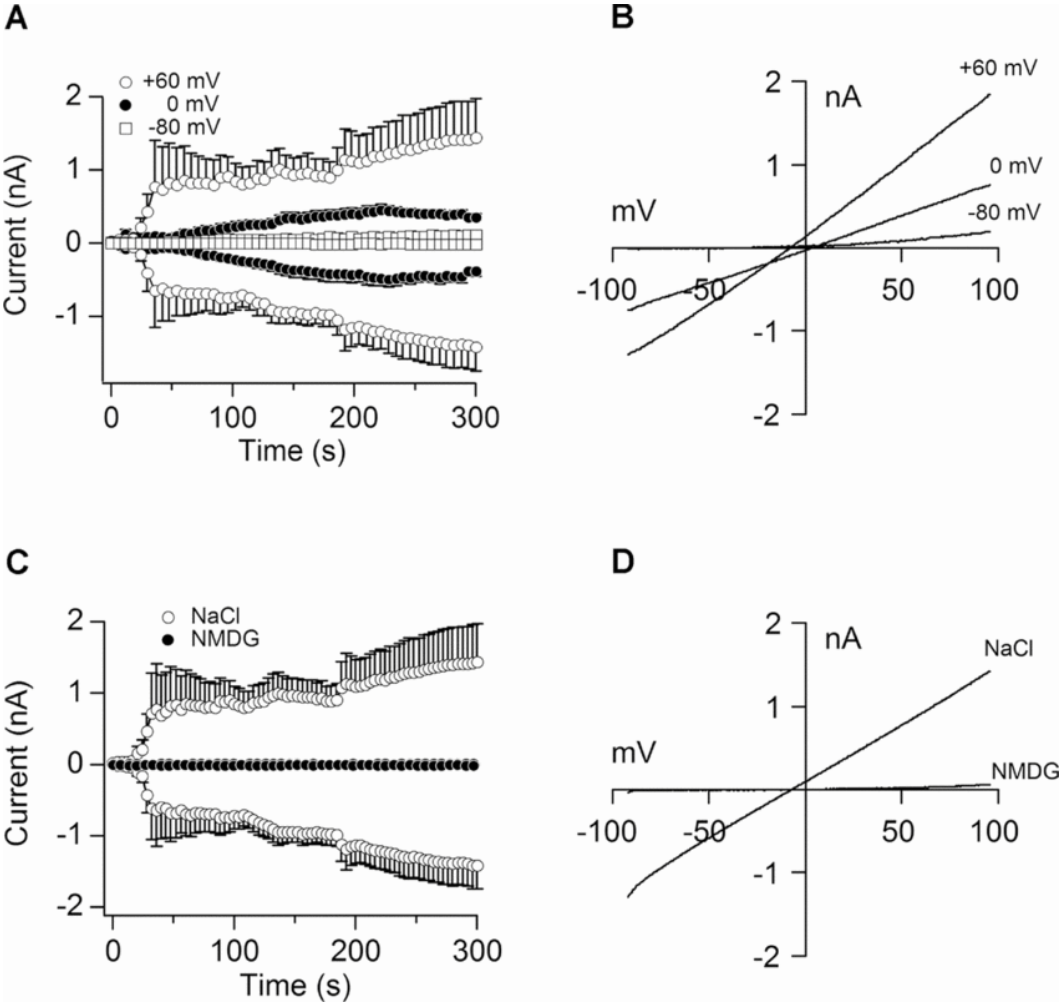

Figure 3.2 Voltage-dependency and ionic conductivity of TRPM4. (A) Average inward and outward currents under −80 mV, 0 mV and +60 mV holding potentials during perfusion of cells with 1 μM intracellular buffered Ca^{2+} concentration. Traces are means±S.E.M. (*n*=3–8 cells per holding potential). (B) *I–V* relationship under experimental conditions described in (A) obtained from representative cells at 300 s. (C) Replacement of NaCl by NMDG in the extracellular buffer solution inhibited TRPM4 currents. Average inward and outward currents from hASCs maintained in control NaCl solution compared with NMDG solution during perfusion with 1 μM intracellular buffered Ca^{2+} concentration at +60 mV holding potential. Traces are means±S.E.M. (*n*=3–8 cells per condition). (D) *I–V* relationship under experimental conditions described in (C) taken from representative cells at 300 s.

3.3.4 Molecular suppression of TRPM4 inhibits channel activity

To determine the importance of TRPM4 for adipogenesis and Ca^{2+} signalling, we have generated stable knockdown cells using shRNA and a

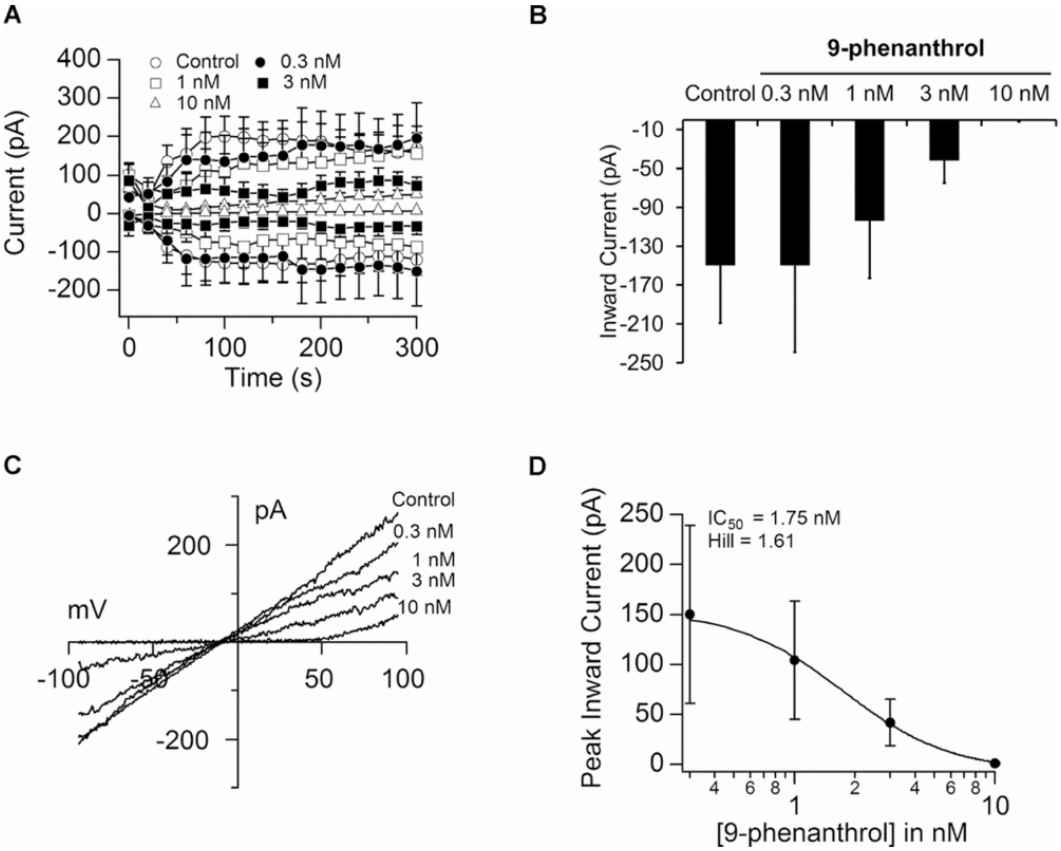

Figure 3.3 Pharmacological suppression of TRPM4 by 9-phenanthrol. (A) Pre-treatment of cells with the specific TRPM4 blocker 9-phenanthrol inhibited channel currents in a concentration-dependent manner during perfusion of cells with 1 μM buffered Ca^{2+} concentration and 0 mV holding potential. (B) Average peak inward currents from cells represented in (A) and compared with control cells without blocker. (C) *I–V* relationship under experimental condition described in (A) obtained from representative cells at 300 s. (D) Calculated IC_{50} and Hill coefficient for different 9-phenanthrol concentrations. Traces represent means±S.E.M. (*n*=6–18 cells per concentration).

lentiviral vector as a delivery agent. The goal of this approach is to obtain cells with reduced TRPM4 activity, which is confirmed by the current amplitude during electrophysiological recordings. We have compared TRPM4 currents between control cells transduced with a scramble sequence shRNA and specific TRPM4 shRNA cells during perfusion with 1 μM intracellular buffered Ca^{2+} concentration at +60 mV holding potential. The currents under these conditions were reduced

significantly with TRPM4 knockdown (Figures 3.4,A and 3.4,B). This confirmed the inhibitory effect of shRNA on channel activity.

3.3.5 TRPM4 suppression decreases lipid droplet accumulation and adipocyte gene expression during adipogenesis

Lipid droplet accumulation is a well-accepted marker for adipocyte differentiation [41]. Hence, we have performed a differentiation assay using Oil Red O staining to determine whether there were differences between control shRNA and TRPM4 knockdown cells after 21 days in adipogenic medium. In accordance with our previous findings in rDFSCs, molecular suppression of TRPM4 significantly reduced lipid droplet accumulation over a 21-day period of differentiation (Figure 3.4,C). In addition, TRPM4 knockdown with two different sets of shRNAs decreased the expression of CCAAT/enhancer-binding protein α (C/EBPα), C/EBPβ, PPARγ2, adipocyte fatty acid-binding protein (aP2) and adiponectin, which are adipocyte marker genes (Figure 3.4,D).

3.3.6 TRPM4 affects Ca^{2+} signalling in response to histamine stimulation

An increase in intracellular Ca^{2+} signals is often seen during stem cell differentiation and is important for this process. Therefore, we have tested whether inhibition of TRPM4 activity in hASCs affected Ca^{2+} signals upon agonist stimulation. We have selected histamine due to its ability to increase intracellular Ca^{2+} and stimulate differentiation of stem cells [42–44]. Stimulation of control wild type cells with 1–300 μM histamine resulted in a concentration-dependent increase in the $[Ca^{2+}]_i$ with maximum responses at 300 μM (Figures 3.5,A and 3.5,B). Next, we examined the histamine receptor mediating the increases using the 300 μM. Pre-treatment of wild-type cells with 10 μM chlorpheniramine, a histamine receptor 1

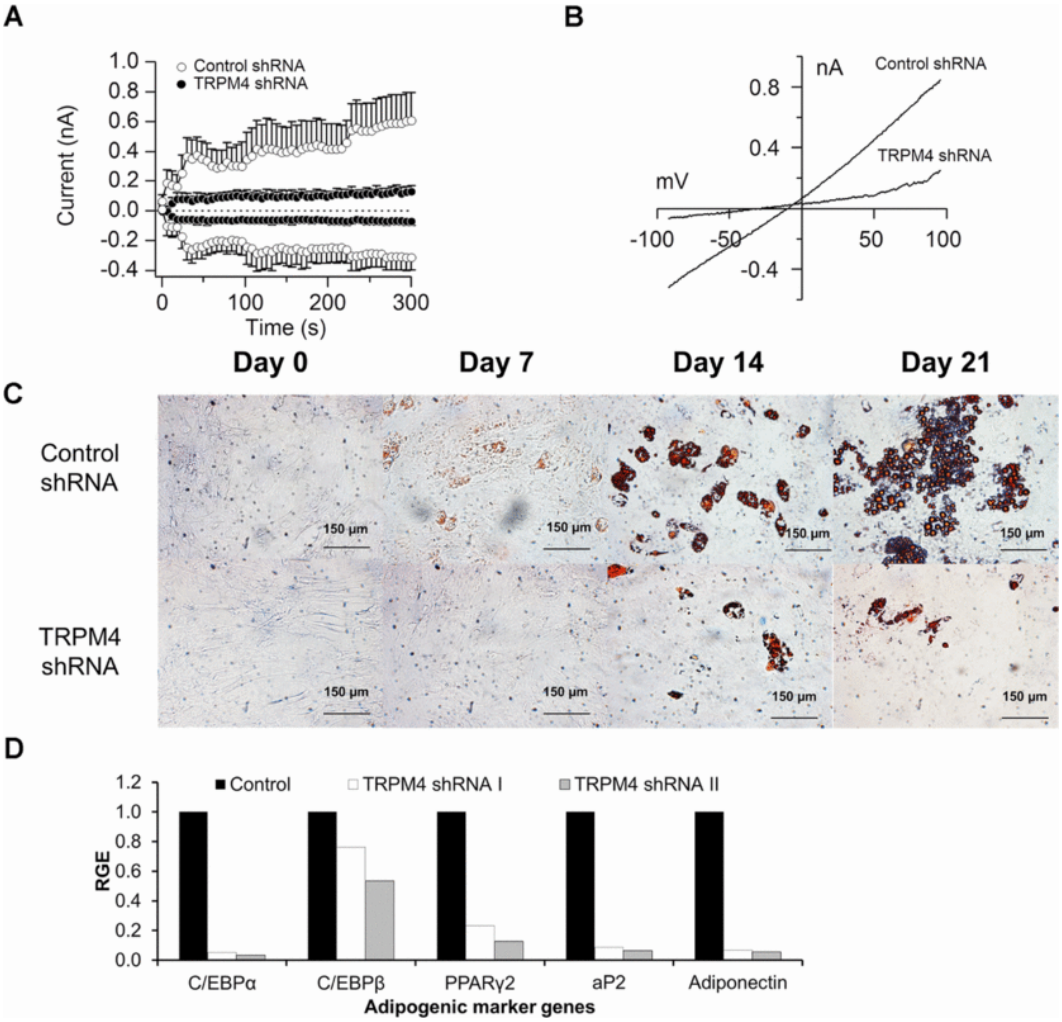

Figure 3.4 TRPM4 knockdown by shRNA inhibits adipocyte differentiation. (A) Inhibition of TRPM4 activity was confirmed by the decrease in the current amplitude under 1 µM intracellular buffered Ca^{2+} concentration and +60 mV holding potential and compared with control shRNA cells. (B) *I–V* relationship under experimental conditions described in (A) obtained from representative cells at 300 s. Traces represent means±S.E.M. [*n*=5 (control shRNA) and 6 (TRPM4 shRNA) cells]. (C) Control shRNA and knockdown cells differentiated into adipocytes for 21 days and stained with Oil Red O for the presence of lipid droplets (×20 magnification). Note the reduction in lipid droplet accumulation with TRPM4 suppression. (D) Molecular suppression of TRPM4 with two different sets of shRNAs decreased adipocyte marker gene expression compared with control cells after 14 days in adipocyte differentiation medium.

(H1) receptor antagonist, completely abolished the Ca^{2+} signals generated by histamine, but not 100 µM cimetidine, an H2 antagonist (Figures 3.5,C–3.5,E). Because TRPM4 is reported to control Ca^{2+} signals in both excitable and non-

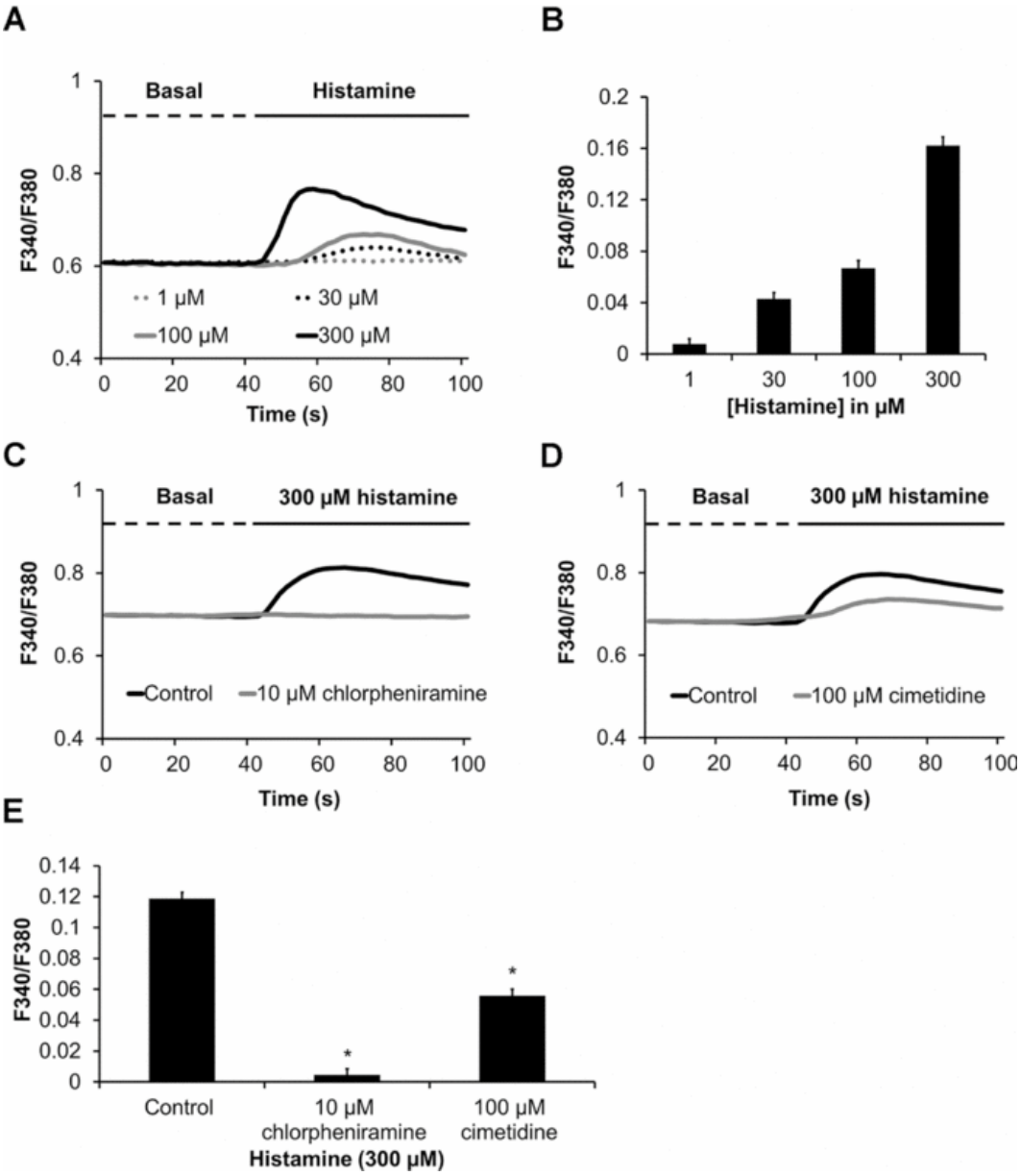

Figure 3.5 Histamine-induced increases in intracellular Ca^{2+} concentration. (A) Average Ca^{2+} signals during stimulation of hASCs with increasing histamine concentrations. (B) Average peak increases for each histamine concentration. (C–D) The inhibitory effects of chlorpheniramine and cimetidine on histamine-induced Ca^{2+} signals are shown. (E) Average peak increases after treatment of cells with the respective receptor blocker and compared with control cells without blocker. Values are means±S.E.M.; *n*=49–272 cells per group from three separate experiments; **P*< 0.0001.

excitable cells, we have tested whether channel suppression would alter the signals generated by histamine. Indeed, TRPM4 knockdown significantly decreased the

responses to 300 μM histamine during adipogenic differentiation (Figures 3.6,A–3.6,D).

3.3.7 TRPM4-mediated depolarization facilitates the opening of VDCCs

Inhibition of TRPM4 activity in hASCs decreased the magnitude of the Ca^{2+} signals compared with control shRNA cells (Figure 3.6). This effect was similar to the ones observed in excitable cells of the pancreas [5, 9] that rely on depolarization and the opening of VDCCs for Ca^{2+} influx. Hence, we have examined *VDCC* gene expression in hASCs using RT–PCR analysis. The results revealed that the L-type $Ca_v1.2$ channel was the main VDCC expressed in this stem cell (Figure 3.7,A). We have also detected $Ca_v1.2$ protein along with TRPM4 (Figure 3.7,B). To determine whether it contributed to Ca^{2+} influx, we have performed Ca^{2+} imaging analysis with nimodipine, an L-type Ca^{2+} channel blocker during histamine stimulation. Pre-treatment with 1–30 μM nimodipine decreased the amplitude of the Ca^{2+} signals compared with control wild-type cells without the blocker but did not abolish the signals even at the highest concentration (Figures 3.7,C–3.7,G). Therefore, we have investigated the additional Ca^{2+} source and confirmed the involvement of TRPM4 in VDCC activation by comparing the responses to histamine under extracellular Ca^{2+}-free conditions and after depletion of endoplasmic reticulum (ER) Ca^{2+} with thapsigargin (Figure 3.7,H). Under control conditions with $CaCl_2$ in the extracellular buffer and without thapsigargin, TRPM4-knockdown decreased the magnitude of the Ca^{2+} signals compared with control shRNA cells. When the extracellular Ca^{2+} was removed from the buffer solution, both control shRNA and TRPM4-knockdown cells had reduced but

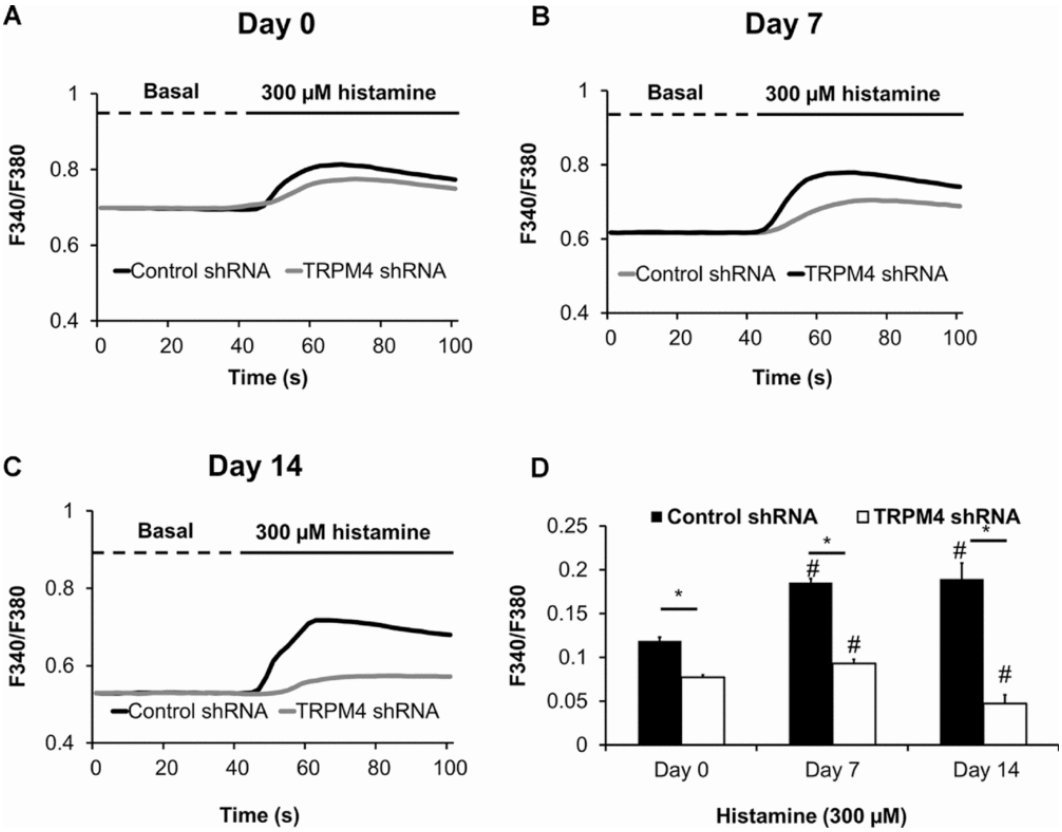

Figure 3.6 TRPM4 knockdown decreases the magnitude of the Ca^{2+} signals by histamine during adipogenesis. (A–C) Average Ca^{2+} signals generated by histamine in control shRNA and TRPM4 knockdown cells at days 0, 7 and 14 of differentiation. (D) Comparison between the average peak Ca^{2+} increases from control shRNA and TRPM4 knockdown cells at the same time point and compared with day 0. Values are means±S.E.M.; *n*=37–338 cells from three separate experiments; **P*<0.05 comparing control and knockdown at the same time point; #*P*<0.05 comparing same group with day 0.

comparable responses. Pre-treatment of cells with thapsigargin almost abolished the responses to histamine in both groups. This indicated that the mechanism by histamine increased intracellular Ca^{2+} was initiated by ER release followed by influx, and the opening of VDCCs was facilitated by TRPM4.

3.3.8 Histamine stimulates adipocyte differentiation

Since histamine stimulates the differentiation of other types of stem cells [42–44], we have examined whether it would affect adipogenesis in hASCs.

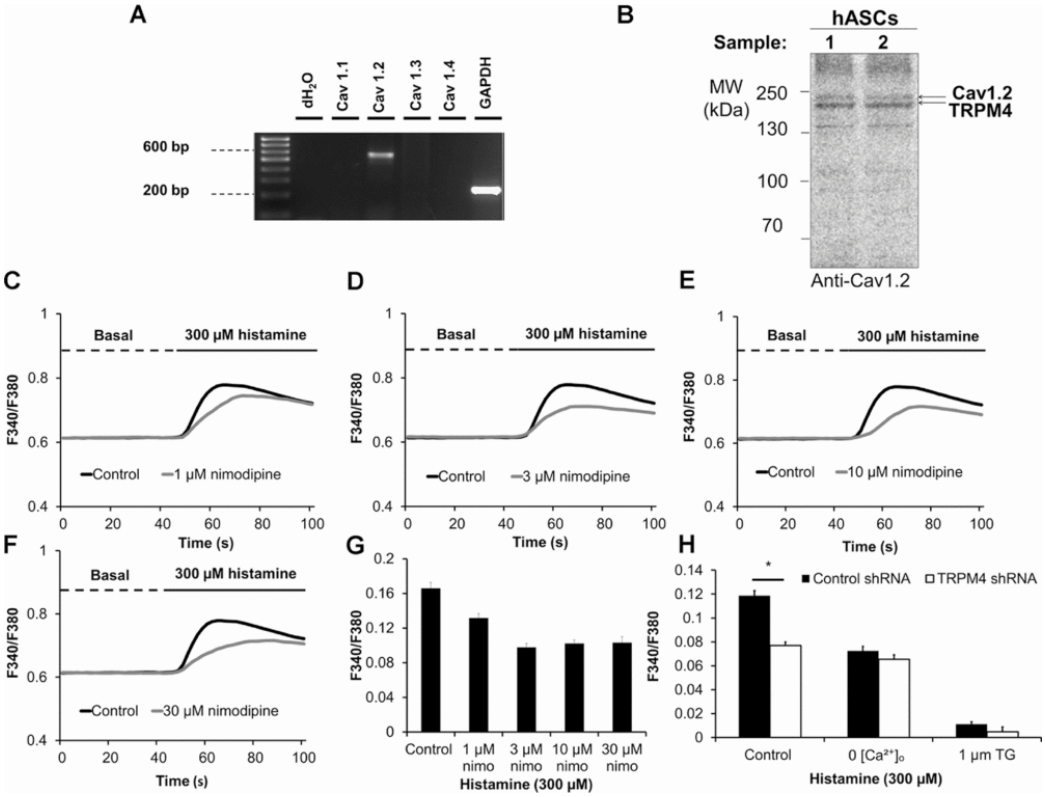

Figure 3.7 hASCs express VDCCs and utilize different Ca^{2+} sources for histamine responses. (A) We have detected $Ca_v1.2$ gene expression in wild-type hASCs, an L-type VDCC, but not $Ca_v1.1$, $Ca_v1.3$ or $Ca_v1.4$. Distilled water and glyceraldehyde-3-phosphate dehydrogenase (GAPDH) served as negative and positive controls respectively. (B) In addition to TRPM4 protein, we have also detected $Ca_v1.2$ protein in two different hASC lines using Western blot analysis. (C–F) Pre-treatment of wild-type cells with increasing nimodipine concentrations, an L-type VDCC blocker, reduced the magnitude of the Ca^{2+}signals in response to histamine stimulation but did not abolished them. (G) Average peak Ca^{2+} increases by histamine after VDCC channel blockage with different nimodipine concentrations and compared with controls cells without the blocker. (H) Comparison between peak Ca^{2+} signals from control shRNA and TRPM4 knockdown cells during histamine stimulation under extracellular free Ca^{2+} condition and after depletion of intracellular Ca^{2+} stores with thapsigargin. Values are means±S.E.M.; *n*=132–338 cells from three separate experiments; **P*<0.001 comparing control shRNA and TRPM4 shRNA cells under same experimental condition.

Histamine (200 nM) supplementation to the adipogenic medium significantly increased lipid droplet accumulation and the number of adipocytes after 14 days of

differentiation compared with control medium without histamine (Figures 3.8,A–3.8,C). These results confirmed its stimulatory effect on the differentiation process.

3.4 DISCUSSION

In a recent report, we have described the presence of TRPM4 in rDFSCs and demonstrated that the channel is required for adipogenesis [6]. Since hASCs are the normal precursors for adipocytes, we have investigated TRPM4 in this type of stem cell. We have identified TRPM4 gene expression and protein in hASCs and human adipose tissue. We have also ruled out the possibility of TRPM5 affecting differentiation and functioning of these cells since hASCs and adipocytes did not express this particular channel. Our findings that adipose tissue expresses TRPM4 suggest a potential role in adipocytes. In fact, white and brown adipocytes have Ca^{2+}-activated non-selective cation (CAN) channels with similar characteristics of TRPM4, such as Ca^{2+}-dependent activation, conductivity, reversal potential and voltage-dependency [45–47]. However, none of these CANs have been recognized until now and it is possible that some might be TRPM4. Furthermore, perfusion of hASCs with increasing buffered Ca^{2+}concentrations activated TRPM4 in a concentration-dependent manner. The calculated EC_{50} value and Hill coefficient of 0.9 μM and 9.09 are very similar to the ones in rDFSCs. Additional characterization of TRPM4 in other stem cells is needed to determine whether there are differences in biophysical properties. In hASCs, we have confirmed TRPM4's voltage-dependency, where negative holding potential inhibited and positive holding potential facilitated channel activity [5, 9]. The channel also conducted Na^+ as the main ion since its replacement by NMDG

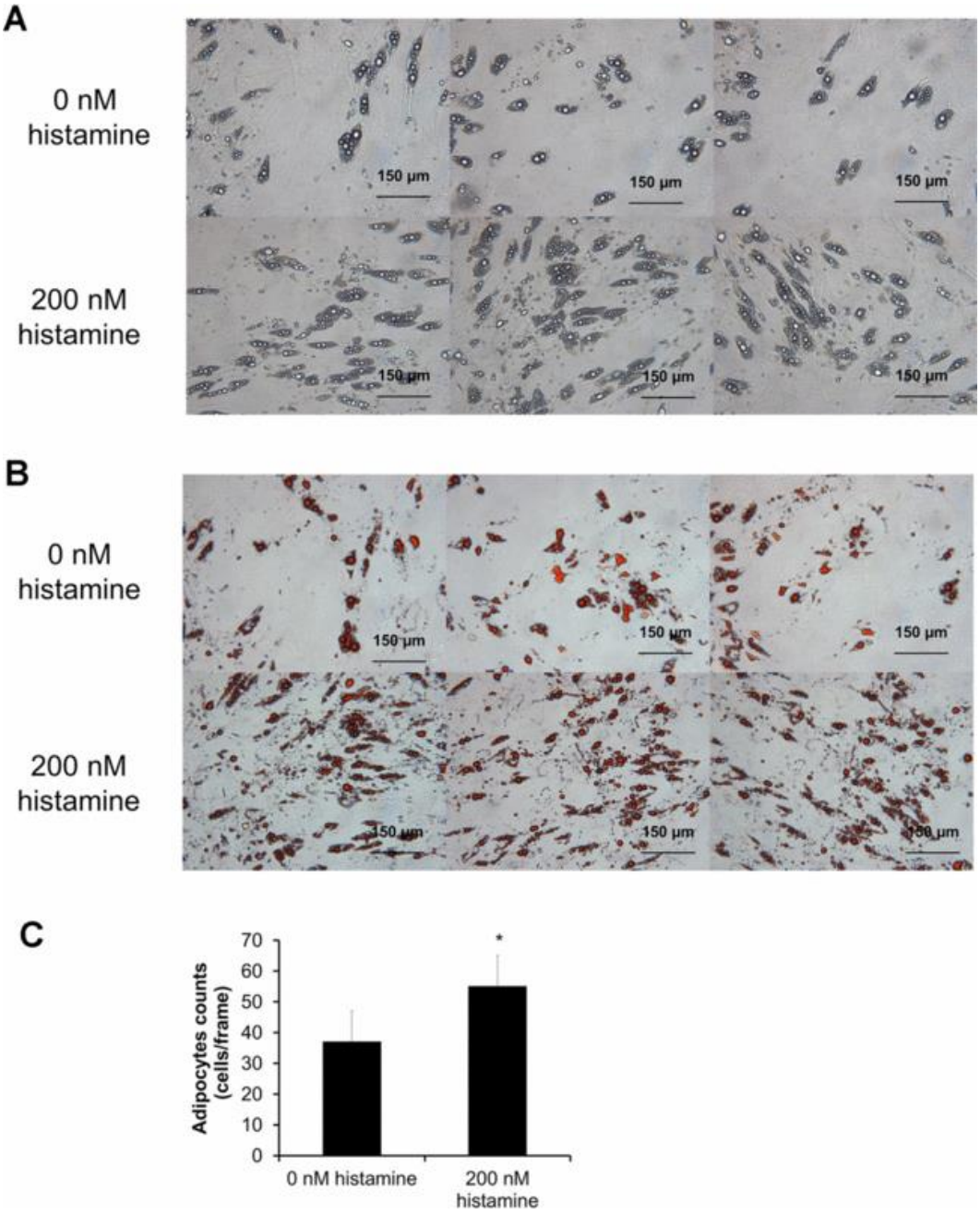

Figure 3.8 Histamine stimulates adipogenesis in hASCs. Wild-type cells were differentiated into adipocytes for 14 days with and without 200 nM histamine in the adipogenic medium and stained with Oil Red O for the presence of lipid droplets (×20 magnification). Note the increase in lipid droplet accumulation with histamine supplementation. (A) Brightfield. (B) Oil Red O staining. (C) Average adipocytes counted from a total of 18 frames taken at ×10 magnification. Values are means±S.E.M.; n=667 (− histamine) and 991 (+ histamine) cells; *P<0.0001.

resulted in complete current suppression. The specific blocker 9-phenanthrol inhibited TRPM4 activity in a concentration-dependent manner. These results showed that the channel is not only is expressed in hASCs but also is functionally active.

To investigate TRPM4's impact on adipogenesis, we have generated stable knockdown cells with the use of shRNA. This approach significantly reduced channel activity as confirmed by patch-clamp recordings. When TRPM4-knockdown cells were cultured in adipogenic medium, there was decreased lipid droplet accumulation and expression of adipocyte marker genes. As with rDFSCs, this is evidence that adipogenesis in hASCs is dependent on functional TRPM4 channels. This process may require TRPM4 activity alone or in combination with other proteins. Heteromultimerization of TRPM4 with sulfonylurea receptor 1 (SUR1) increases channel sensitivity to intracellular Ca^{2+} and affinity to calmodulin [48]. These Ca^{2+} signals are reported to activate transcription factors and enzymes involved in adipogenesis [e.g. PPARγ and fatty acid synthase (FAS)] and to suppress adipolysis [49–51]. Other TRPM family members such as TRPM7 are important for proliferation and conversion of pre-adipocyte cells into the mature adipocyte [52]. Using RT–PCR, we have identified *TRPM6* and *TRPM7* gene expressions in hASCs and human adipose tissue; however, their roles remain to be determined.

One of the goals of the present study was to provide insight into the Ca^{2+} signalling mechanism controlling adipogenesis in hASCs. Using histamine, a well-known activator of Ca^{2+} signals and regulator of stem cell differentiation, we

have found that TRPM4 suppression reduced the magnitude of the signals compared with control shRNA cells. This was an unexpected finding since TRPM4 knockdown in rDFSCs enhances Ca^{2+} signalling. From this observation, we have reasoned that hASCs use VDCCs as their main pathway for Ca^{2+} influx (excitable cells) instead of SOCs (non-excitable cells) [53]. This is supported by findings in pancreatic α- and β-cells, where TRPM4 suppression decreases the magnitude of Ca^{2+} signals generated by agonist stimulation [5, 9]. In non-excitable cells, the opposite occurs when TRPM4 is inhibited because depolarization decreases the driving force for Ca^{2+} entry via SOCs [6, 7, 54]. In support of our excitable cell hypothesis, we have found that hASCs expressed the $Ca_v1.2$ channel, a main type of VDCC. Furthermore, the VDCC blocker (nimodipine) decreased the magnitude of the Ca^{2+}signals generated by histamine. These findings suggested that Ca^{2+} influx via the $Ca_v1.2$ channel is a component of the Ca^{2+} signals. Experiments under extracellular Ca^{2+}-free conditions and after depletion of the intracellular Ca^{2+}stores were performed to examine additional Ca^{2+} sources. From our data, it was clear that TRPM4 is required for the full histamine response since channel knockdown reduced the magnitude of the Ca^{2+} signals. Experiments in the absence of extracellular Ca^{2+} had a similar effect to TRPM4 knockdown. This can be explained by the fact that TRPM4 depolarization opens VDCCs resulting in Ca^{2+} influx. Without Ca^{2+} in the extracellular buffer or TRPM4 activity there is no influx. When the intracellular Ca^{2+} stores were depleted using thapsigargin, the Ca^{2+} signals were abolished regardless of whether or not TRPM4 was suppressed. These Ca^{2+} signals generated by histamine in hASCs are typical of G_q-coupled receptors that increase

inositol 1,4,5-trisphosphate (IP_3) formation and mobilize intracellular Ca^{2+} from the ER. This initial Ca^{2+} release is likely to activate TRPM4, which depolarizes the cell leading to the opening of VDCCs to further increase the magnitude of the Ca^{2+} signals and stimulate PPARγ and FAS during adipogenesis according to the proposed mechanism shown in Figure 3.9. This would explain in part why TRPM4 knockdown inhibited adipogenesis in hASCs. Despite the differences in the Ca^{2+} signalling pattern between rDFSCs and hASCs, both showed decreased lipid droplet accumulation and expression of adipocyte marker genes with channel knockdown. This raises the possibility that other factors that are not Ca^{2+}-dependent but are linked to TRPM4 may control adipogenesis.

Another interesting finding was the presence of two histamine receptors (H1 and H2) in hASCs as determined using chlorpheniramine and cimetidine. From our results, H1 receptors seem to be the most predominant since chlorpheniramine completely inhibited the Ca^{2+} signals, whereas cimetidine reduced the responses by 50%. Both receptors, especially H1, are critical for differentiation. For example, H1 receptors are up-regulated during 3T3-L1 fibroblast differentiation and antagonists or receptor knockdown inhibits insulin-induced adipogenesis [51]. Histamine increases dendritic cell differentiation via H1 and H2 receptors becausereceptor blockage reduces the expression of differentiation markers [42]. In another study, H1 is the most important for monocyte differentiation despite the expression of H2 [55]. Histamine also increases the expression of receptor activator of nuclear factor κB ligand during osteoclastogenesis via H1 receptors [56]. Both

receptor types are critical for histamine-induced neural stem cell proliferation and differentiation [44].

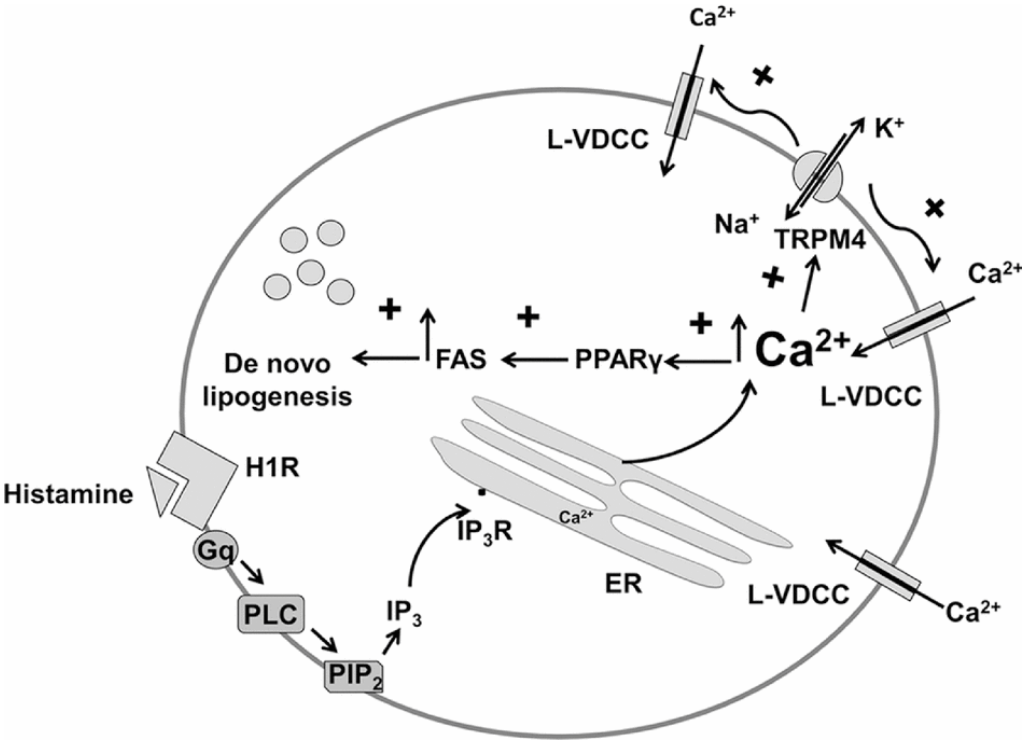

Figure 3.9 Proposed mechanism for histamine and TRPM4 control of Ca^{2+} signalling and adipogenesis in hASCs. Activation of histamine receptors, mainly the H1 type, increases intracellular Ca^{2+} via G_q-proteins and the phospholipase C (PLC)/IP_3 pathway. The initial Ca^{2+} release from the ER activates TRPM4, which depolarizes cells leading to the opening of VDCCs and Ca^{2+} influx. The Ca^{2+} release and influx are the sources for the Ca^{2+} signals that could control the activation of transcription factors and enzymes involved in adipogenesis.

In addition to H1/H2, the H4 receptor is described in bone marrow mesenchymal stem cells; however, only H1 mediates the Ca^{2+} signals [57]. Based on our findings and reports by other laboratories, we have found that the increases in intracellular Ca^{2+} mainly via H1 receptors are essential for adipocyte differentiation and/or function.

Conclusions

We have characterized for the first time TRPM4 in hASCs and demonstrated its importance for histamine-induced Ca^{2+} signalling and adipogenesis. The mechanism appears to involve in part Ca^{2+} release from the ER and influx via VDCCs with TRPM4 providing the depolarization necessary to activate the channel. The excitable cell characteristic of hASCs was a surprising finding since most undifferentiated stem cells are known to be of the non-excitable type.

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CHAPTER 4: ARGININE VASOPRESSIN INHIBITS ADIPOGENESIS IN HUMAN ADIPOSE-DERIVED STEM CELLS*

4.1 INTRODUCTION

Arginine vasopressin (AVP) is synthesized in the paraventricular and supraoptic nucleus of the hypothalamus and is secreted from the posterior pituitary gland mainly in response to dehydration. It is also detected in ovaries, adrenal gland, testis, thymus and pancreas [1-5]. AVP mediates its effects via three G protein-coupled receptors, the V1a, V1b, and V2. The V1a receptor can be found in lymphocytes, smooth muscle and mesangial cells [6-8]. The V1b receptor is present in pancreatic α and β cells, astrocytes and adrenal medulla [9-12]. In addition, AVP binds to V2 receptors in the renal distal tubule and collecting duct cells to promote water reabsorption during dehydration by activating the cAMP pathway [13]. Important physiological roles for AVP include platelet aggregation, liver glycogenolysis, uterine motility, vasoconstriction, cell proliferation and growth. It stimulates protein synthesis via V1a receptors and insulin, glucagon, catecholamine, ACTH secretion via V1b receptors [14]. Activation of V1 receptors has a significant impact on intracellular Ca^{2+} signals because they are coupled to Gq-proteins and the phospholipase C-β (PLC-β) and inositol triphosphate (IP_3) pathway. Increases in IP_3 result in Ca^{2+} release from the endoplasmic reticulum (ER) and influx from the extracellular space [15]. Calcium oscillations are required for cell proliferation and differentiation, because it activates transcription factors,

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such as nuclear factor of activated T-cells (NFAT) [16]. Translocation of NFAT adipogenic and into the nucleus is observed during stem cell differentiation, but ends at terminal stages of osteogenic differentiation [17, 18]. Elevation in intracellular Ca^{2+} inhibits adipocyte formation during early stages of differentiation, but facilitates it at later stages [19, 20]. An increase in Ca^{2+} influx activates the mitogen-activated protein kinase (MAPK) pathway to stimulate osteogenic differentiation in mesenchymal stem cells [18]. Calcium signaling is essential for embryonic and mesenchymal stem cell cycle progression via the G_1/S phase [21-23]. They up-regulate peroxisome proliferator-activated receptor γ (PPARγ) gene expression, a master transcription factor for adipogenesis. PPARγ increases fatty acid synthase activity and triacylglycerol production in lipid droplets [19]. Other studies revealed a stimulatory effect of AVP on myoblast and T-cell differentiation via V1 receptors [8, 24, 25]. However, AVP inhibits osteoclast differentiation [26].

Other physiological functions for AVP include control of thermogenesis by increasing UCP-1 protein expression for uncoupling oxidative phosphorylation during heat production from brown fat [27]. Studies in V1a receptor knockout mice show enhanced lipid metabolism, muscle proteolysis and insulin signaling suppression that is supported by observations of impaired glucose tolerance in these animals [28]. The anti-lipolytic effect is mediated by Ca^{2+} signals and the MAPK pathway [27, 29]. A reduction in adiponectin mRNA is detected after adipocyte stimulation with AVP [27]. This hormone also inhibits ketogenesis by suppressing β-oxidation of fatty acid [30]. Pathophysiological conditions such as hypertension and obesity are associated with reduced plasma AVP [31, 32]. Obese and sedentary

individuals have lower AVP levels compared to lean ones, whereas exercise increases hormone secretion [33, 34]. This observation is confirmed in patients before and after weight loss [35]. The same study reported an inverse correlation between AVP and insulin that is consistent with the knowledge that obese nondiabetic individuals have increased insulin and adipose tissue but low AVP levels. Patients with multiple symmetric lipomatosis due to alcohol abuse exhibit large symmetrical accumulation of non-capsulated fat tissue that is associated with reduced AVP secretion caused by alcohol [36]. Interestingly, nicotine stimulates AVP secretion and may in part explain why cigarette smokers gain weight after they stop smoking [37]. Although Ca^{2+} signals are reported in hASCs [38], the mechanism by which AVP increases intracellular Ca^{2+} and its role on adipogenesis is unknown. In this study, we characterized the AVP receptor subtype, its signaling pathway and impact on adipocyte differentiation.

4.2 MATERIALS AND METHODS

4.2.1 Reagents

All reagents were purchased from Sigma Chemical Co. (St. Louis, MO, USA), except that fura-2 acetoxymethyl ester (Fura-2AM) was from Anaspec (Fremont, CA, USA), d-calcium pantothenate was from Fisher Scientific (Pittsburgh, PA, USA), [Arg8] vasopressin (AVP) from American Peptide Co. (Sunnyvale, CA, USA) and 2-APB from Cayman Chemical Co. **(**Ann Arbor, MI, USA).

4.2.2 Cell culture

Human adipose-derived stem cells were isolated from lipoaspirates of abdomen, breast adipose tissues, right knee and right scapula donated by consenting two Caucasian females and a male, age from 34 to 66 years old, BMI from 23.5 to 33.78 under a protocol reviewed and approved by the Pennington Biomedical Institutional Review Board (#PBRC23040) and maintained in Dulbecco's modified Eagles medium (DMEM)/Ham's F-12 medium with 10% fetal bovine serum (FBS) (Atlanta Biologicals, Lawrenceville, GA, USA) and aerated with 5% CO_2 at 37°C. All experiments were performed with cells from passages 3-8.

4.2.3 RT-PCR

Total RNA was extracted using the RNAqueous-4PCR® kit according to the manufacturer's instructions (Ambion, Austin, TX, USA). The RNA was treated with DNase 1 to remove DNA contamination. Reverse transcription and PCR were performed using Ambion's RETROscript® kit. The human PCR primers (forward/reverse [5'–3']) are listed in Table 4.1. Human glyceraldehyde-3-phosphate dehydrogenase (GAPDH) and dH_2O were used as positive and negative controls, respectively.

Table 4.1 List of primers of AVP receptor genes for RT-PCR

Gene	Forward primer (5'-3')	Reverse primer (5'-3')	Size (bp)
C/EBPα	CGGTGGACAAGAACAGCAAC	CGGAATCTCCTAGTCCTGGC	365
C/EBPβ	CACAGCGACGACTGCAAGATCC	CTTGAACAAGTTCCGCAGGGTG	188
PPARγ2	GCTGTTATGGGTGAAACTCTG	ATAAGGTGGAGATGCAGGTTC	325
aP2	TGGTTGATTTTCCATCCCAT	TACTGGGCCAGGAATTTGAT	150

(Table 4.1 continued)

Gene	Forward primer (5'-3')	Reverse primer (5'-3')	Size (bp)
Adiponectin	GGCCGTGATGGCAG AGAT	TTTCACCGATGTCTCC CTTAGG	88
LPL	GAGATTTCTCTGTAT GGCACC	CTGCAAATGAGACACT TTCTC	276
Leptin	GGCTTTGGCCCTATC TTTTC	GCTCTTAGAGAAGGCC AGCA	325
Cyclophilin B	GGAGATGGCACAGG AGGAAA	CGTAGTGCTTCAGTTT GAAGTTCTCA	72

4.2.4 Quantitative RT-PCR

From each sample, 2μg of total RNA was reverse-transcribed into 20μl of cDNA. Each PCR was prepared by mixing 2μl of the cDNA with 2x SYBR Green PCR master mix (Bio-Rad, Hercules, CA, USA) and gene-specific primers (Table 4.2). The PCR was carried out with ABI 7300 real-time PCR system (Life Technologies, Grand Island, NY, USA) to obtain the C_T value. Relative gene expression (RGE) was calculated by the delta C_T method using β-actin as the endogenous control for normalization and cyclophilin B as the reference control with an RGE of 1.

Table 4.2 List of primers of adipogenic marker genes for quantitative RT-PCR

Gene	Forward primer (5'-3')	Reverse primer (5'-3')	Size (bp)
AVP V1a receptor	CAGGTGTTCGGCATG TTTG	ACCAGATGTTGTAGCA GATGAA	343
AVP V1b receptor	CTCATCTGCCATGAG ATCTGTAA	CCACATCTGGACACTG AAGAA	249
AVP V2 receptor	ATTCATGCCAGTCTG GTGC	TCACGATGAAGTGTCC TTGG	422
GAPDH	AACAGCGACACCCA CTCCTC	GGAGGGGAGATTCAG TGTGGT	258

4.2.5 Calcium imaging analysis

Cells were loaded with 2μM Fura-2AM for 30 min at 37°C. The imaging buffer containing (in mM): NaCl 136, KCl 4.8, $CaCl_2$ 1.2, $MgSO_4$ 1.2, HEPES 10, glucose 4, and 0.1% BSA, pH 7.3 was used for Fura-2AM loading and perfusion throughout the experiments. Calcium measurements were obtained using a dual excitation fluorometric imaging system (TILL-Photonics, Gräfefingen, Germany) controlled by TILLvisION software. Fura-2AM loaded cells in perfusion chamber were excited by 340nm and 380nm wavelengths. Fluorescence emissions were sampled at a frequency of 1 Hz and computed into relative ratio units of the fluorescence intensity of the difference of wavelengths (F340/F380). Data were expressed as averages from several cells from three separate experiments.

4.2.6 Induction and detection of lipid droplets

Cells reaching between 80% and 90% were induced with differentiation medium containing DMEM/Ham's F-12 supplemented with 3% FBS, 0.25mM 3-isobutyl-1-methylxanthine (IBMX), 33μM biotin, 17μM d-calcium panthothenate, 100nM human insulin, 1μM dexamethasone and 5μM rosiglitazone for 3 days. Adipocyte medium having the same composition as differentiation medium except for IBMX and rosiglitazone was changed every 3 days from day 3 to day 21 [39]. To test the effect of AVP on adipogenesis, 100nM AVP was supplemented to the adipogenic medium and changed every 2 days until day 14 of differentiation. Adipogenesis was determined by Oil Red O (ORO) staining. Briefly, cells were washed with PBS, fixed with 10% formalin for 10 min, washed twice with dH_2O, and incubated with 60% isopropanol for 5 min. Cells were then stained with ORO

solution for 5 min and washed again to remove excess dye. The presence of lipid droplets was visualized by phase contrast microscopy using an inverted microscope (Zeiss, Thornwood, NY, USA).

4.2.7 Data analysis

Adipocyte count was performed from a total of 36 or 18 frames taken at 10x magnification from each group using software ImageJ (1.47v; http://imagej.nih.gov/ij). The peak Ca^{2+} signals and adipocyte counts are shown as means ± S.E.M. and were analyzed using a two-tailed and unpaired Student's *t*-test (GraphPad *Software Inc.*, La Jolla, CA, USA). Statistical significance was established at $P<0.05$.

4.3 RESULTS

4.3.1 hASCs differentiate into adipocytes and express the V1a receptor gene

In order to demonstrate that hASCs can differentiate into adipocytes, we cultured the cells in adipogenic media and examined the differentiated cells with ORO staining at the end of 14 days. Adipogenesis was confirmed by the presence of lipid droplet accumulation (Figure 4.1,A). Next, we examined the type of AVP receptor in hASCs at day 0 and 14 of differentiation. RT-PCR analysis revealed V1a receptor gene expression, but not V1b or V2 (Figure 4.1,B).

4.3.2 AVP increases intracellular Ca^{2+} in hASCs under growth and adipogenic conditions

Since hASCs expressed the V1a receptor before and after differentiation, we performed real-time Ca^{2+} imaging analysis to investigate the responses to AVP. Stimulation of cells with 1μM AVP increased intracellular Ca^{2+} at days 0, 7, 14 and 21 of differentiation (Figure 4.2,A). However, there was a greater response to AVP

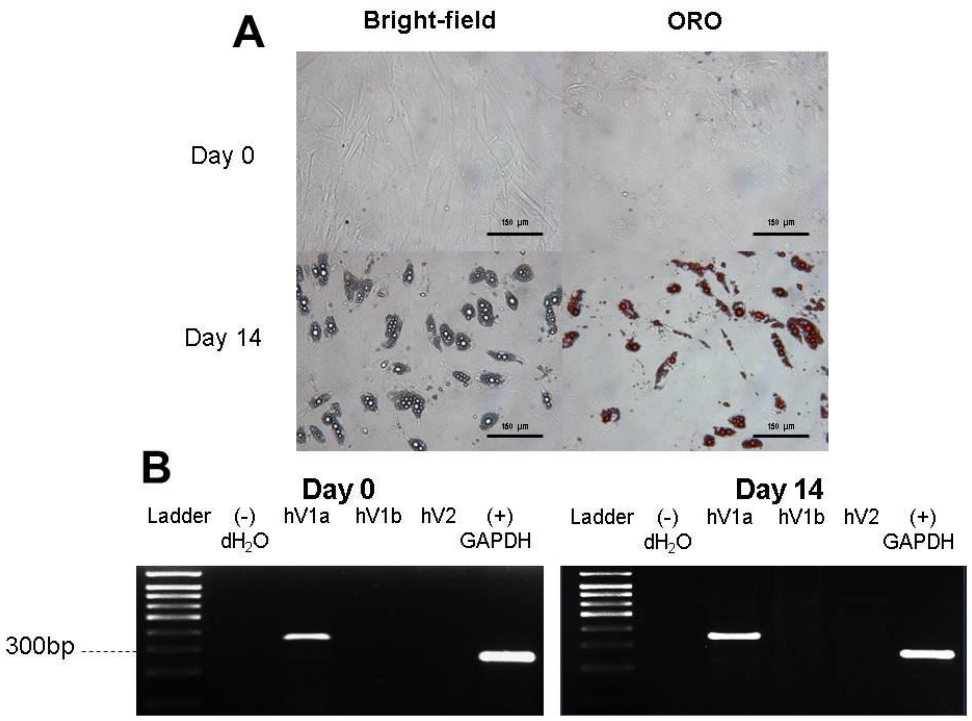

Figure 4.1 hASCs differentiation into adipocytes and expression of the V1a receptor gene. (A) hASCs were differentiated into adipocytes for 14 days and stained with Oil Red O (ORO) for the presence of lipid droplets (20x magnification). (B) hASCs expressed the V1a receptor gene at day 0 and day 14 of differentiation. RT-PCR was performed with specific human V1a, V1b, V2 primers. dH_2O and GAPDH served as negative and positive controls, respectively.

at day 14 compared to day 21 of differentiation (Figure 4.2,B). Therefore, we chose day 14 for our experiments since at this time period, we also detected adipocyte differentiation. To confirm the AVP responses in hASCs, cells were stimulated with 0.003-1µM AVP that resulted in a concentration-dependent increase in $[Ca^{2+}]_i$ with a peak at 1µM concentration (Figure 4.2,C and D). In order to test whether the V1a receptor indeed mediated the effect of AVP, cells were pretreated with 0.0001-1µM V2255, a selective V1a receptor antagonist. V2255 inhibited the Ca^{2+} signals in a concentration-dependent manner in both undifferentiated and differentiated cells (Figure 4.3,A-D).

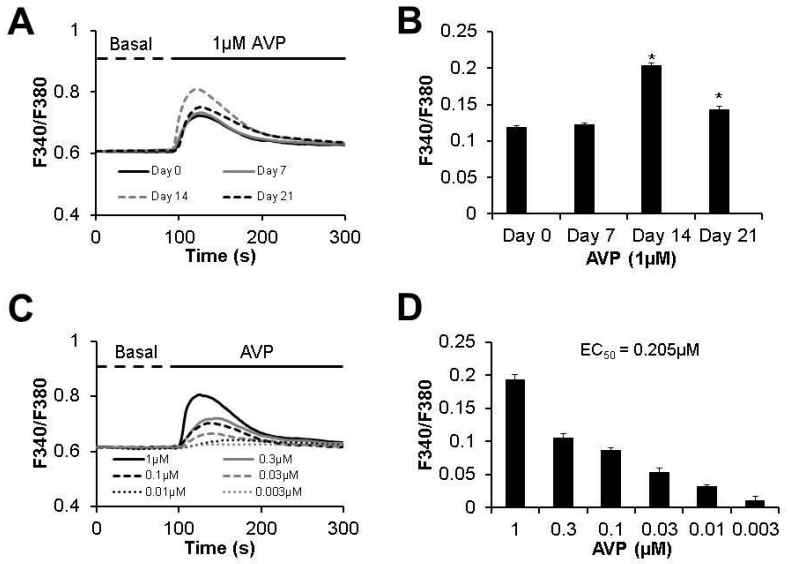

Figure 4.2 hASCs are responsive to AVP prior to and during adipogenesis**.** (A) Average Ca^{2+} signals in response to AVP from day 0 to day 21 of differentiation. (B) The AVP response increased until day 14, but decreased at day 21. (C) Average Ca^{2+} signals in response to increasing AVP concentration. (D) Average peak responses to different AVP concentrations. Values are means ± S.E.M.; n = 86-705 cells; * P<0.0001 compared to day 0.

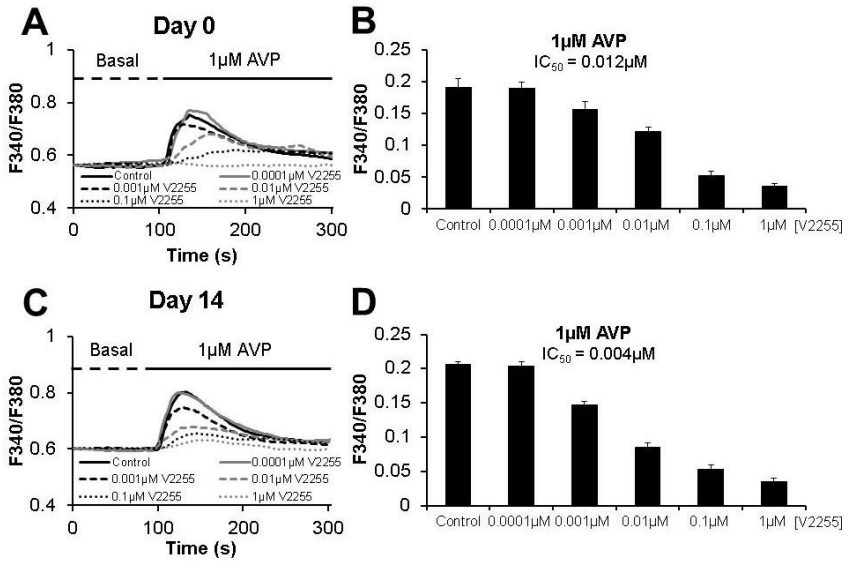

Figure 4.3 The V1a receptor mediates AVP signaling in hASCs. (A, B) Average traces and peak Ca^{2+} signals generated by AVP after V2255, a selective V1a blocker pretreatment at day 0. (C, D) Same experiments as in A and B, except at day 14 of adipogenic differentiation. Values are means ± S.E.M.; n = 51-433 cells/concentration.

4.3.3 AVP increases intracellular Ca^{2+} via the PLC-IP_3 pathway

AVP stimulates Ca^{2+} signals via the V1a receptor in smooth muscle and intestinal epithelial cells by activating the phospholipase C enzyme (PLC) [40, 41].Therefore, we utilized the PLC blocker, U73122 to test whether it could inhibit AVP signaling. U73122 (2-12µM) pretreatment for 5 min inhibited the responses to AVP in a concentration-dependent manner (Figure 4.4,A and B). Pretreatment of cells with U73343, an inactive analog of U73122 did not alter the responses to AVP (Figure 4.4,C and D). Since IP_3 is a downstream second messenger to PLC,

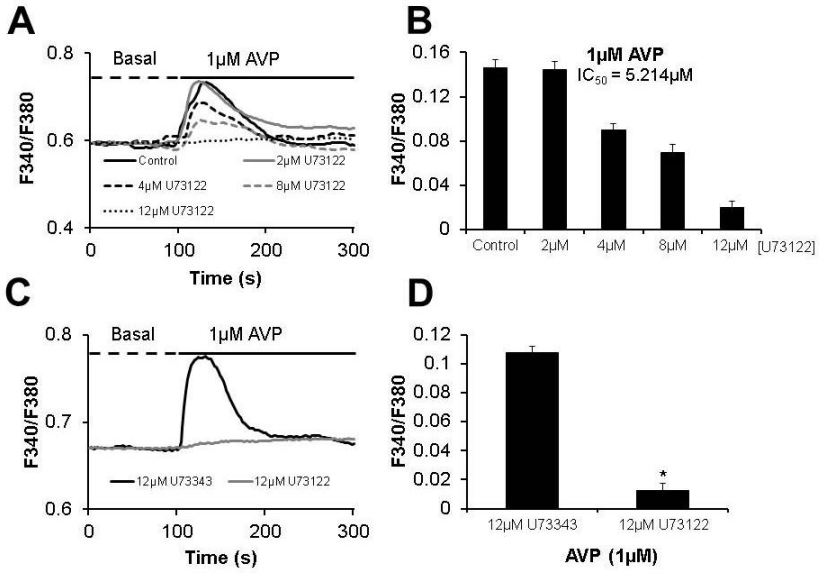

Figure 4.4 Involvement of PLC in the AVP mechanism in hASCs. (A, B) Averages and peak Ca^{2+} signals generated by AVP after pretreatment of cells with the PLC inhibitor, U73122. (C, D) Averages and peak Ca^{2+} signals after pretreatment with U73343, an inactive analog of U73122. Values are means ± S.E.M.; n = 59-81 cells/concentration; * P<0.0001.

we utilized 2-APB, an IP_3 receptor blocker. Pretreatment of cells for 5 min with 10-300µM 2-APB inhibited the responses to AVP in a concentration-dependent manner (Figure 4.5,A and B). In addition, we compared the maximum AVP

response in hASCs to those of 2μM ionomycin and 100μM ATP, another Gq-coupled receptor agonist (Figure 4.5,C and D).

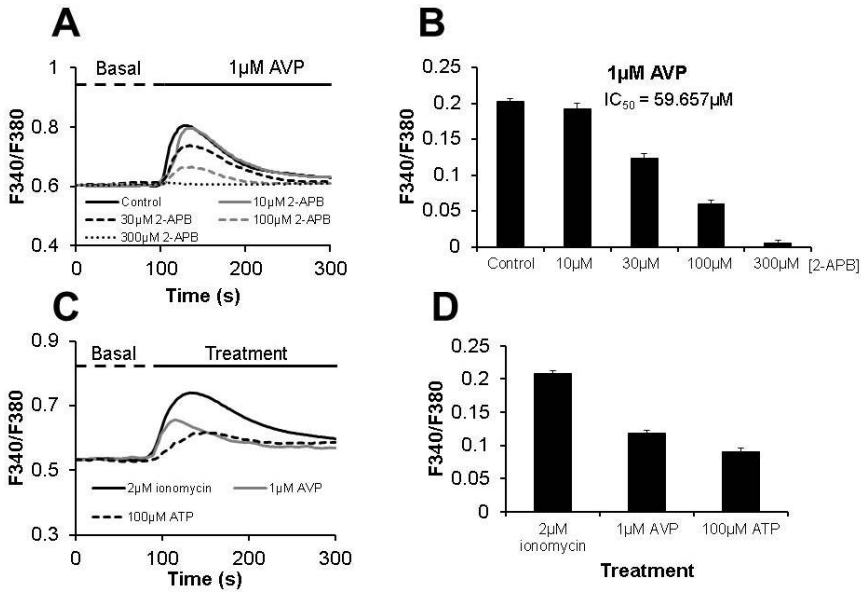

Figure 4.5 IP_3 binding to its receptor initiates the Ca^{2+} signals. (A, B) Average Ca^{2+} signals and peak responses after pretreatment of cells with 2-ABP, a selective IP_3 receptor blocker. Values are means ± S.E.M.; n = 77-705 cells/concentration. (C, D) Average Ca^{2+} signals and peak responses induced by ionomycin, AVP and ATP in hASCs. Values are means ± S.E.M.; n = 102-131 cells/concentration.

4.3.4 Sources of Ca^{2+} for AVP signals

In bone marrow-derived stem cells, Ca^{2+} influx and release from the ER generate the Ca^{2+} signals [42]. Hence, we tested in hASCs the contribution of extracellular Ca^{2+} on AVP signaling by performing experiments under Ca^{2+} free buffer condition. Removal of extracellular Ca^{2+} significantly reduced the Ca^{2+} signals compared to control cells in Ca^{2+} containing buffer (Figure 4.6,A). Next, we pretreated cells with thapsigargin (TG) for 20 min, a Ca^{2+}-ATPase pump inhibitor in the ER to investigate the impact of intracellular Ca^{2+} on AVP signals. Depletion of Ca^{2+} stores with TG completely abolished the responses to AVP (Figure 4.6,B).

Under extracellular free Ca^{2+} and TG conditions, AVP also failed to increase intracellular Ca^{2+} (Figure 4.6,C and D).

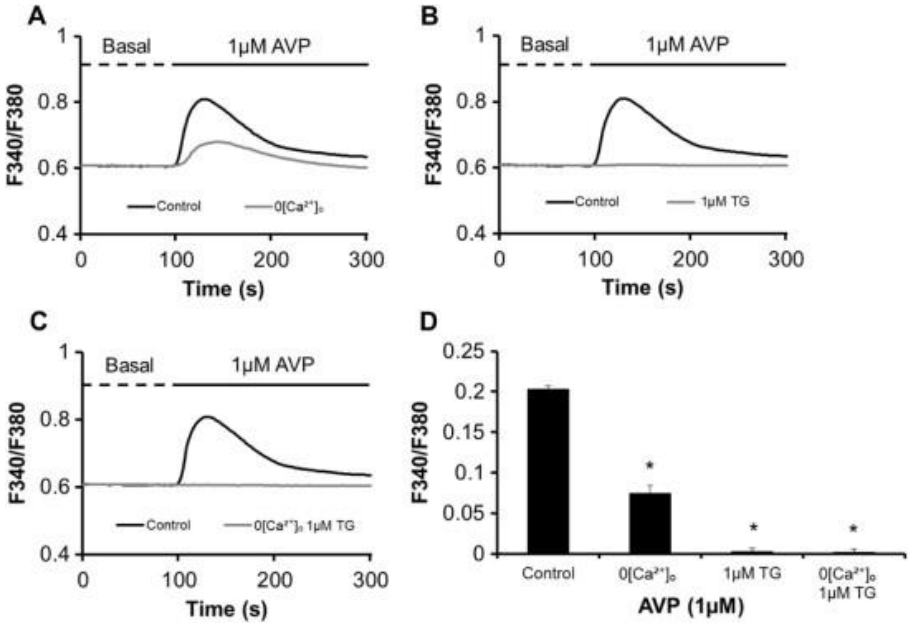

Figure 4.6 Intracellular Ca^{2+} release and influx are sources for the Ca^{2+} signals. (A) Average Ca^{2+} signals during AVP stimulation under extracellular Ca^{2+} and Ca^{2+} free conditions. (B) Depletion of ER Ca^{2+} stores with thapsigargin (TG) abolished the AVP responses. (C) Experiments performed under extracellular Ca^{2+} free condition and TG simultaneously. (D) Average peak responses from experiments in A–C. Values are means ± S.E.M; n = 63-705 cells/treatment; * P<0.0001 compared to peak control group.

4.3.5 AVP inhibits adipogenesis during hASC differentiation

To investigate the effect of AVP on adipogenesis, we supplemented the differentiation medium with 100nM AVP which enhances differentiation of other cell types [24, 43, 44]. AVP supplementation reduced lipid droplet accumulation as determined by ORO staining (Figure 4.7,A-C) and decreased adipocyte formation compared to control cells without AVP (Figure 4.7,D). The hormone also decreased the expression of adipocyte marker genes: CCAAT/enhancer-binding protein α (C/EBPα), CCAAT/ enhancer-binding protein β (C/EBPβ), peroxisome proliferator-activated receptor γ 2 (PPARγ2), adipocyte protein 2 (aP2),

adiponectin, lipoprotein lipase (LPL) and leptin compared to control group without AVP after 14 days of differentiation (Figure 4.8).

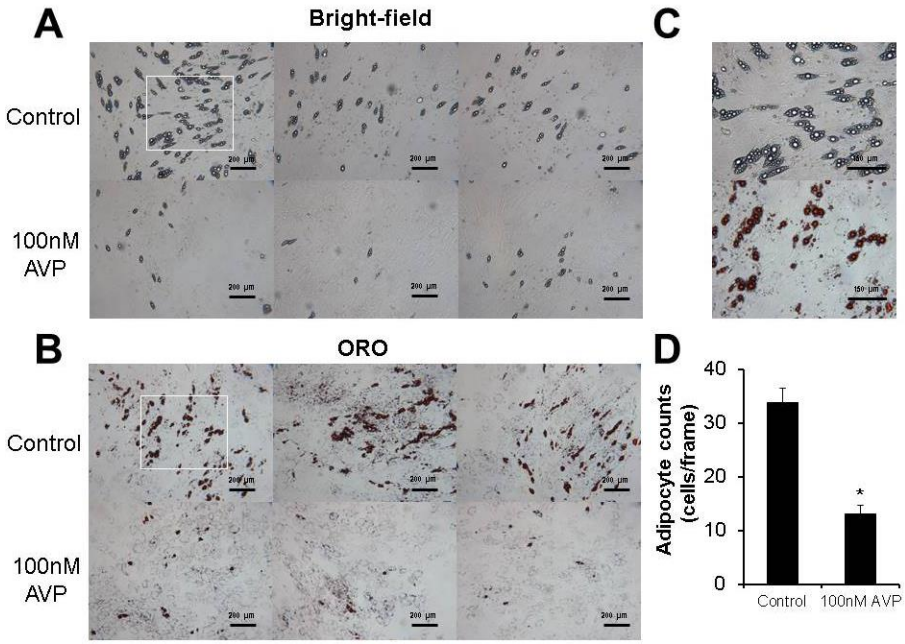

Figure 4.7 AVP inhibits adipogenesis during hASC differentiation. (A, B) Bright-field and ORO staining images taken at day 14 of differentiation from AVP treated and control group without AVP (10x magnification). (C) Adipocyte morphology shown at 20x magnification from cells in A and B. (D) Adipocyte count per frame from a total of 36 frames from each group. Values are means ± S.E.M; n = 471 (+AVP) and 1213 (-AVP) cells; * P<0.0001.

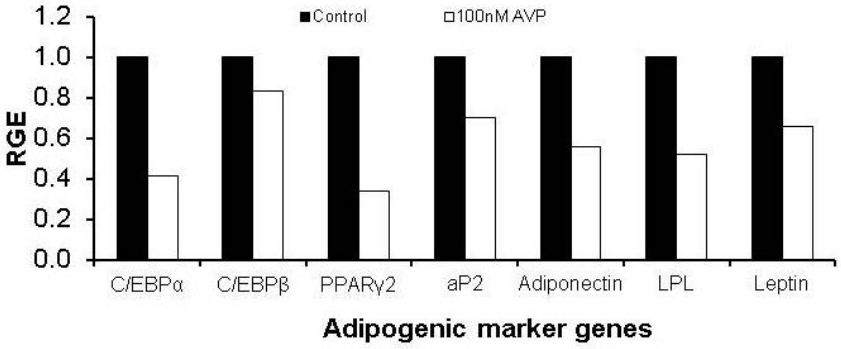

Figure 4.8 AVP down-regulates adipocyte marker genes in hASCs. Stimulation of cells with AVP during 14 days of adipogenic differentiation decreased the expression of adipocyte marker genes compared to control cells in the absence of AVP.

4.3.6 V1a receptor blocker V2255 reverses the effect of AVP on adipogenesis

Finally, to confirm the effect of AVP on adipocyte differentiation we performed adipogenic experiments with the V1a receptor blocker V2255. AVP (100nM) supplementation significantly reduced the number of adipocytes as indicated by lipid droplet accumulation and ORO staining. When V2255 (100μM) was added to the differentiation medium along with AVP, it reversed the inhibitory effect of AVP on adipogenesis (Figure 4.9,A and B). In the study, V2255 alone did not alter adipocyte formation.

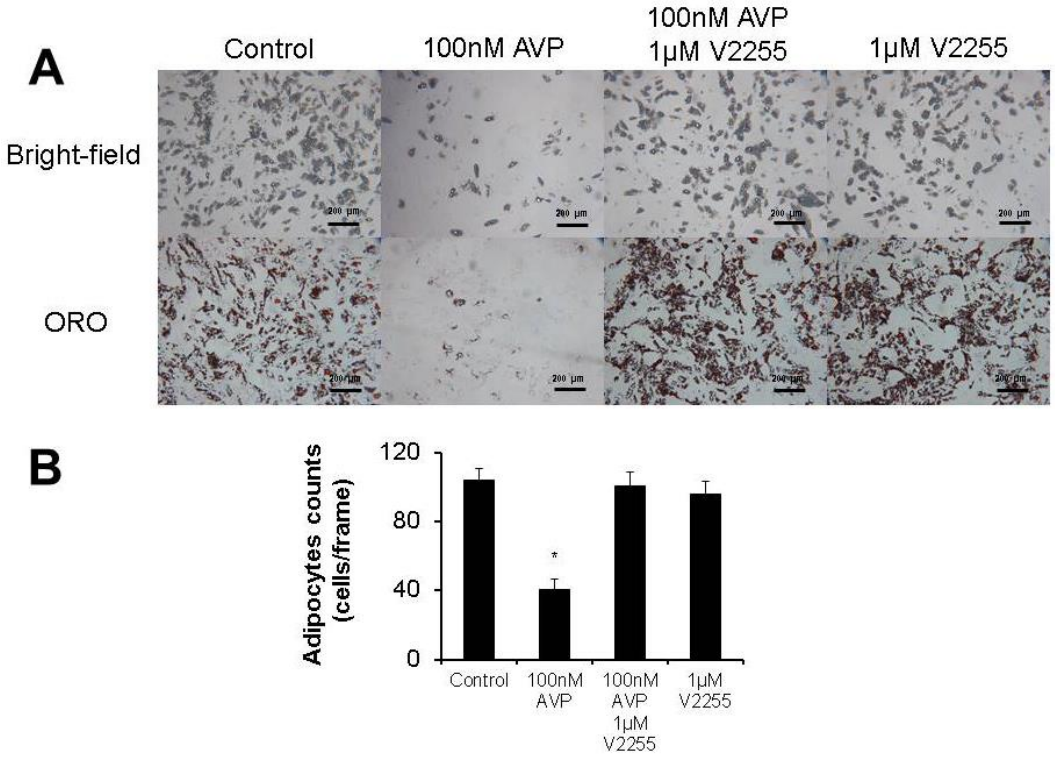

Figure 4.9 V1a receptor blocker reverses the effect of AVP on adipogenesis. (A) Bright-field and ORO staining images taken at day 10 of differentiation from control adipogenic medium alone and AVP, AVP+V2255 or V2255 supplemented groups (10x magnification). (B) Adipocyte count per frame from a total of 18 frames from each group. Values are means ± S.E.M; n = 1869 (control adipogenic medium), 725 (+AVP), 1805 (+AVP and V2255), and 1723 (+V2255) cells; * $P<0.001$.

4.4 DISCUSSION

The role of AVP (a.k.a. anti-diuretic hormone) in water conservation during dehydration is well established. It acts by promoting translocation into the plasma membrane of tubular cells to allow water reabsorption [45]. Other studies revealed that the hormone is capable of stimulating cellular growth and proliferation. Despite the identification of AVP receptors in stem cells [44], its function in Ca^{2+} signaling and differentiation remains largely unexplored. We investigated the mechanism of AVP signaling and its impact on adipocyte differentiation in hASCs, which is a well-accepted stem cell type for adipogenic studies [46]. When placed in adipogenic medium, accumulation of lipid droplets can be evidenced within the cell population that resembles the characteristics of mature adipocytes. We demonstrated that undifferentiated hASCs and differentiated adipocytes express the V1a receptor, but not the V1b or V2. This observation differs from mouse embryonic stem cells that express all three receptor subtypes [44]. It is possible that the pluripotent nature of embryonic stem cells compared to multipotent adult stem cells may be accountable for this variation. The possibility of AVP receptor variation among species also needs to be considered. Since V1a receptors are coupled to Gq-proteins that utilize the PLC-IP3 pathway and Ca^{2+} signaling [47-49], we examined whether the Ca^{2+} signals observed in hASCs during AVP stimulation was a result of this mechanism. In addition, we investigated the impact of the hormone on adipocyte differentiation.

Initial experiments demonstrated that hASCs are responsive to AVP throughout the differentiation process, with a peak Ca^{2+} increase at day 14, but

decreases at day 21. Other types of adult stem cells (e.g. bone marrow derived) exhibit similar Ca^{2+} signaling pattern during the terminal stages of osteoblast and adipocyte differentiation [17, 18]. It is reasoned that these signals are important for directing and terminating the differentiation process. Furthermore, we confirmed the V1a receptor as the type mediating the effect of AVP before and after differentiation. The V1a receptor blocker V2255 inhibited the responses to AVP in a concentration-dependent manner, which is consistent with the RT-PCR data showing V1a gene expression in hASCs. Since receptors coupled to Gq proteins in hASCs activate the PLC enzyme [38], we utilized U73122, a PLC inhibitor to test whether it mediated the effects of AVP. Indeed, pretreatment of cells with U73122 inhibited the Ca^{2+} signals, but not U73343, an inactive analog. Next, we examined the effect of IP_3 a downstream second messenger to PLC on ER Ca^{2+} release. Pretreatment of cells with 2-APB, an IP3 receptor blocker inhibited the AVP responses in a concentration-dependent manner. These findings revealed that the mechanism by which AVP signals in hASCs is by activating V1a receptors and the PLC-IP3 pathway. In view that 2-APB abolished the AVP response, it indicated that ER Ca^{2+} release was a source for the Ca^{2+} signals. To test this hypothesis and to determine whether extracellular Ca^{2+} was involved, we performed experiments with TG and under extracellular Ca^{2+} free conditions. Depletion of Ca^{2+} stores by TG resulted in a complete suppression of the AVP responses, but not in the absence of extracellular Ca^{2+}. Under both conditions, AVP also failed to increase intracellular Ca^{2+}. From these results, it is clear that both Ca^{2+} release and influx are required for AVP signaling in hASCs. While most of the Ca^{2+} appears to come

from the extracellular space, the ER release is needed to initiate the process. These observations are consistent with those reported for Gq-coupled receptor hormones that utilize the PLC-IP_3 pathway. This mechanism involves both Ca^{2+} release from the ER followed by the opening of store-operated Ca^{2+} channels in the plasma membrane via the Ca^{2+} sensor STIM-1 and Orai1 [50, 51]. One important question that needed to be addressed was the effect of AVP on adipogenesis. This was determined by supplementing the adipogenic differentiation medium with AVP followed by adipocyte quantification and marker gene expression in the cell population. The data demonstrated an inhibitory effect of AVP on adipogenesis since the number of adipocytes was significantly reduced. In addition, key adipogenic marker genes (e.g. C/EBPα, C/EBPβ, PPARγ2) were down-regulated. It is possible that AVP's effect on adipogenesis may involve MAPK/Erk signaling since this pathway is activated by the hormone and V1a receptors [52, 53]. This is supported by findings in bone marrow-derived stem cells where inhibition of MAPK/Erk facilitates adipocyte differentiation [54, 55]. Furthermore, MAPK/Erk signaling phosphorylates PPARγ leading to decreased transcriptional activity and suppression of adipogenesis [56]. Most importantly, Ca^{2+} signals inhibit adipogenesis by down-regulating C/EBPα, C/EBPβ, C/EBPγ and PPARγ genes in preadipocytes via MAPK/Erk [57].

Based on our results and those presented by others, it appears that AVP exerts mainly an inhibitory effect on adipocyte metabolism and differentiation. This is based on the fact that the absence of V1a receptor in knockout mice enhances lipolysis but decreases glucose uptake by adipocytes [28, 58]. AVP also inhibits β-

oxidation of fatty acid as an alternative energy source for the body [30]. The inhibitory effect of AVP on adipocyte differentiation could be reversed by the V1a receptor blocker V2255 which confirms its role on adipogenesis. It is tempting to speculate that the reduction in plasma AVP levels during obesity or multiple symmetric lipomatosis might be one of the factors responsible for adipose tissue accumulation/formation. Additional studies in V1a receptor knockout mice and humans with V1a receptor mutation show a tendency to develop obesity and diabetes [59, 60]. A link between AVP and body weight gain in cigarette smokers after quitting has been established due to the stimulatory action of nicotine on AVP secretion [37]. These observations together with our findings in hASCs could provide insights into new therapies for obesity.

In conclusion, we have identified the V1a receptor as the only type for AVP in hASCs. This receptor mediates the effect of AVP on intracellular Ca^{2+} signaling by activating Gq-proteins and the PLC-IP_3 pathway. This mechanism appears to exert an inhibitory effect on adipogenesis by down-regulating the expression of key adipogenic genes.

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CHAPTER 5: CONCLUDING REMARKS

5.1 SUMMARY OF FINDINGS AND SIGNIFICANCE OF THE RESEARCH

Calcium signaling plays an important role in many cell functions such as differentiation, proliferation, apoptosis, and muscle contraction [1]. Chapter 1 of this dissertation summarizes the different types of stem cells, the Ca^{2+} signaling mechanisms, the TRPM4 channel and AVP's impact on Ca^{2+} signals. We utilized rDFSCs and hASCs to investigate the role of TRPM4 and AVP on stem cell differentiation. Chapter 2 describes our findings on the role of TRPM4 in rDFSCs. We generated TRPM4 knockdown cells to investigate its effect on osteogenesis and adipogenesis. After 14 days in differentiation media, TRPM4 knockdown showed enhanced mineralization and decreased lipid droplet accumulation. Microarray analysis revealed upregulation of critical genes for bone formation such as LUM and MEPE, and downregulation of ASPN, which inhibits differentiation and mineralization [2]. Several adipogenic genes, for example, TRIB3 and SFRP1, decreased in expression; TRIB3 is crucial for adipocyte formation and SFRP1 enhances adipogenesis in human and mice [3, 4]. The Ca^{2+} signals generated by ATP changed from a biphasic pattern to a gradual and sustained increase with TRPM4 inhibition. Therefore, we identified for the first time TRPM4 in stem cells and demonstrated that it is a key regulator of Ca^{2+} signals that facilitates adipogenesis but inhibits osteogenesis in rDFSCs.

As hASCs are a more suitable model for adipogenic studies, we investigated the role of TRPM4 in these cells in Chapter 3. We identified TRPM4 gene expression in hASCs and human adipose tissue. We also characterized the channel

in these cells. Our findings from the adipogenic studies were similar to those in rDFSCs since TRPM4 knockdown inhibited adipocyte formation and decreased adipocyte marker genes (PPARγ2, C/EBPα, C/EBPβ, aP2 and adiponectin). However, the Ca^{2+} signals with TRPM4 knockdown were different from rDFSCs and resembles those observed in pancreatic α and β cells which are excitable cells. We found that hASC gene expressed the L-type VDCCs ($Ca_v1.2$) which contributed to Ca^{2+} signals stimulated by histamine. This is important since undifferentiated stem cells are considered as non-excitable cells with SOCs as their main Ca^{2+} entry pathway [5]. The difference in the Ca^{2+} pattern between rDFSCs and hASCs may be due to the type of MSCs, species or impact of other pathways during differentiation.

In Chapter 4, we investigated the effect of AVP on adipogenesis of hASCs. We showed for the first time V1a receptor gene expression in hASCs. AVP in this stem cell type inhibited adipogenesis. This is in accordance to V1a receptor mutation or knockout that leads to obesity and diabetes [6, 7]. Our result provides insight into the mechanism of AVP on adipogenesis.

The decrease in intracellular Ca^{2+} during histamine stimulation in hASCs after TRPM4 suppression inhibited adipogenesis and was similar to our findings with AVP supplementation to the adipogenic medium. Therefore, it is likely that other signaling pathways may contribute to this process. In fact, Ca^{2+} signaling can crosstalk with other pathways such as cAMP because Ca^{2+} release from the ER activates STIM1 and increases cAMP signaling [8]. Activation of the V1a receptor by AVP also stimulates phosphatidylcholine hydrolysis by phospholipase A2. This

results in arachidonic acid production, increased phospholipase D and Na^+/H^+ exchanger activity. These effects control gene expression and protein synthesis during the differentiation process [9].

5.2 FUTURE STUDIES

TRPM4 facilitates adipogenesis, but inhibits osteogenesis in rDFSCs. To confirm these observations, we will rescue TRPM4 expression and perform a differentiation experiment to determine if the effect can be reversed in TRPM4 knockdown cells. To do that, we will design TRPM4 siRNA against the 3′-untranslated regions (UTR) of the endogenous TRPM4 gene. Then, we will transfect a vector containing the coding sequence for TRPM4 without the 3'-UTR. Therefore, TRPM4 overexpression from the vector construct will not be affected by the siRNA whereas the endogenous TRPM4 mRNA will be degraded. We will confirm TRPM4 expression by RT-PCR and Western blot. Functional studies will be performed with patch-clamp, ARS and ORO staining, Ca^{2+} imaging analysis, and quantitative RT-PCR. By patch-clamp, we will compare the amplitude of TRPM4 currents to those of control cells. ARS and ORO staining, Ca^{2+} imaging analysis, and quantitative RT-PCR will be performed during differentiation at days 0, 7, 14, 21 to determine whether the effect of TRPM4 knockdown can be reversed.

Furthermore, we will investigate the effect of TRPM4 *in vivo*. We plan to examine the ability of TRPM4 knockdown rDFSCs in bone repair of critical-size calvarial defects in the rat model. We will use micro-CT imaging, perform histologic analysis, and confirm osteogenic marker gene expression for new bone formation [10]. Regarding a pharmacological approach, 9-phenanthrol, a TRPM4

selective blocker can be toxic to the cells; therefore, it has limited potential in clinical therapy [11]. Other TRPM4 blockers such as flufenamic acid, an anti-inflammatory drug, and glibenclamide, the antidiabetic drug; both have been approved by the FDA [11, 12]. However, they also interact with other ion channels which can cause many side effects. As a consequence, more research needs to be done to identify specific TRPM4 blockers to control obesity and osteoporosis in the future. In conclusion, our results provided insights into the molecular mechanisms controlling stem cell differentiation by the TRPM4 ion channel and the hormone AVP. These findings could potentially lead to new therapies for the treatment of obesity and bone defects.

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